HANDBOOK OF
MRI
TECHNIQUE

THIRD EDITION

Catherine Westbrook

WILEY-BLACKWELL

Handbook of MRI Technique

Handbook of MRI Technique

Third Edition

Catherine Westbrook

Anglia Ruskin University
Cambridge, UK

Contents

Contributors

Catherine Westbrook MSc, DCR(R), PgC (L&T), CT Cert, FHEA
Senior Lecturer and Post-Graduate Course Leader, Radiography, Anglia Ruskin University, Cambridge, UK

John Talbot MSc, DCR(R), PgC (L&T) FHEA
Senior Lecturer, Radiography, Anglia Ruskin University, Cambridge, UK

William Faulkner BS RT(R), (MR) (CT), FSMRT
William Faulkner & Associates, LLC

Carolyn Kaut RT(R), (MR), (CT)(M)(CV),
CEO, Imaging Education Associates

Michael Kean Dip. App. Sci., Grad. Dip. Edu.
Senior Radiographer, Children's MRI Centre, Royal Children's Hospital, Melbourne, Australia
Research Affiliate – Murdoch Childrens Research Institute

Preface

The *Handbook of MRI Technique* is now an established text for many MRI practitioners around the world. *MRI in Practice* (also published by Blackwell Publishing) provides radiographers and radiologists with a user-friendly approach to MRI theory and how it may be applied in practice. The *Handbook of MRI Technique* is intended to guide the uninitiated through scanning techniques and protocols and to help more experienced technologists improve image quality and recognize and rectify common artefacts. In many countries a lack of educational facilities and funding, as well as the complex nature of the subject, has resulted in practitioners experiencing difficulty in learning MRI techniques. The second edition, published in 1999, has filled this gap and has proven to be a useful clinical text. In this, the third edition, it has been my intention to continue with the objectives of the second edition but update the reader on recent technical advances in both hardware and software. As previously, technologists and radiographers from the UK, USA and Australia have made large and important contributions to the book and, as a result, I believe the third edition is even more comprehensive than the second.

The *Handbook of MRI Technique* is split into two parts. Part 1 summarizes the main aspects of theory that relate to scanning and also includes practical tips on gating and equipment use, patient care and safety, and information on contrast media. Several useful tables are added for ease of reference and the pulse sequence section has been updated to include newer sequences. Part 2 includes a step-by-step guide to examining each anatomical area. It covers most of the techniques commonly used in MRI as well as paediatric imaging. Under each examination, categories such as indications, patient positioning, equipment, artefacts and tips on optimizing image quality are included. Guidance on technique and contrast usage is also provided. Owing to the variety of imaging systems and differences in radiological preferences, information on protocols is mainly limited to pulse sequence, scan plane and slice prescription. The advice given on protocols is only intended to direct the examination. In addition, a basic anatomy section has been added at the beginning of each examination area.

The *Handbook of MRI Technique* provides a guide to the operation of MR systems and to enhance the education of MR users. It is not intended to be a clinical book as there are plenty of clinical specialist books on the market. Therefore, apart from the Paediatric chapter in which several

clinical images are to be found, diagrams and images focus intentionally on scan planes, slice prescriptions and sequencing to reflect the technical thrust of the book.

The third edition of the *Handbook of MRI Technique* should be especially beneficial to those technologists studying for board certification or post-graduate and MSc courses, as well as to assistant practitioners, radiographers and radiologists who wish to further their knowledge of MRI techniques. The contributing authors and I hope that it continues to achieve these goals.

Catherine Westbrook

Acknowledgements

1

How to use this book

Introduction

This book has been written with the intention of providing a step-by-step explanation of the most common examinations currently carried out using Magnetic Resonance Imaging (MRI). It is divided into two parts.

Part 1 contains reviews or summaries of those theoretical and practical concepts that are frequently discussed in Part 2. These are:

- parameters and trade-offs
- pulse sequences
- flow phenomena and artefacts
- gating and respiratory compensation techniques
- patient care and safety
- contrast agents.

These summaries are not intended to be comprehensive but contain only a brief description of definitions and uses. For a more detailed discussion of these and other concepts, the reader is referred to the several MRI physics books now available. *MRI in Practice* by C. Westbrook, C. Kaut Roth and John Talbot (Blackwell Science, 2005, third edition) describes them in more depth.

Part 2 is divided into the following examination areas:

- head and neck
- spine
- chest
- abdomen
- pelvis
- upper limb
- lower limb
- paediatric imaging.

Each anatomical region is subdivided into separate examinations. For example, the section entitled *Head and Neck* includes explanations

1

on imaging the brain, temporal lobes, pituitary fossa, etc. Under each examination the following categories are described:

- basic anatomy
- common indications
- equipment
- patient positioning
- suggested protocol
- image optimization.

Basic anatomy

Simple anatomical diagrams are provided for most examination areas to assist the reader.

Common indications

These are the most usual reasons for scanning each area, although occasionally some rarer indications are included.

Equipment

This contains a list of the equipment required for each examination and includes coil type, gating leads, bellows and immobilization devices. The correct use of gating and respiratory compensation is discussed in Part 1 (*see Gating and respiratory compensation techniques*). The coil types described are the most common currently available. These are as follows.

- **Volume coils** that both transmit and receive radio-frequency (RF) pulses and are specifically called transceivers. Most of these coils are quadrature coils, which means that they use two pairs of coils to transmit and receive signal, so improving the signal to noise ratio (SNR). They have the advantages of encompassing large areas of anatomy and yielding a uniform signal across the whole field of view (FOV). The body coil is an example of this type of coil.
- **Phased array coils** consist of multiple coils and receivers. The signal from the receiver of each coil is combined to form one image. This image has the advantages of both a small coil (improved SNR) and those of the larger volume coils (increased coverage). Therefore phased array coils can be used either to examine large areas, such as the entire length of the spinal cord, or to improve signal uniformity and intensity in small areas such as the breast. Phased array coils are commonly used in spinal imaging.

1

- **Surface/Local coils** are traditionally used to improve the SNR when imaging structures near to the skin surface. They are often specially designed to fit a certain area and, in general, they only receive signal. RF is usually transmitted by the body coil when using this type of coil. Surface coils increase SNR compared with volume coils. This is because they are placed close to the region under examination, thereby increasing the signal amplitude generated in the coil, and noise is only received in the vicinity of the coil. However, surface coils only receive signal up to the edges of the coil and to a depth equal to the radius of the coil. To visualize structures deep within the patient either a volume, phased array coil, parallel imaging coils or a local coil inserted into an orifice must be utilized (e.g. a rectal coil).
- **Parallel imaging or multi-coils** use the data from multiple coils or channels arranged around the area under examination to either decrease scan time and/or increase resolution. Additional software and hardware are required. The hardware includes several coils perpendicular to each other or one coil with several channels. The number of coils/channels varies but it is usually a minimum of 2 and maximum of 32. During acquisition each coil fills its own lines of K space (e.g. if 2 coils are used together one coil fills the even lines of K space and the other the odd lines. K space is therefore filled either twice as quickly or with twice the resolution in the same scan time). The number of coils/channels used is called the reduction factor and is similar in principle to the turbo factor/ETL in fast spin echo (*see section on Pulse sequences* in Part 1). Every coil produces a separate image which often displays aliasing artefact (*see section on Artefacts in Part 1*). Software removes aliasing and combines the images from each coil to produce a single image. Most manufacturers offer this technology, which can be used in any examination area and with any sequence. It has special advantages in brain and body imaging.

The choice of coil for any examination is one of the most important factors that determine the resultant SNR of the image. When using any type of coil remember to:

- Check that the cables are intact and undamaged.
- Check that the coil is plugged in properly and that the correct connector box is used.
- Ensure that the receiving side of the coil faces the patient. This is usually labelled on the coil itself. Note: Both sides of the coil receive signal but coils are designed so that one side receives optimum signal. This is especially true of shaped coils that fit a certain anatomical area. If the wrong side of the coil faces the patient, signal is lost and image quality suffers.
- Place the coil as close as possible to the area under examination. The coil should not directly touch the patient's skin as it may become warm during the examination and cause discomfort. A

small foam pad or tissue paper placed between the skin surface and the coil is usually sufficient insulation.

- Ensure that the coil does not move when placed on the patient. A moving coil during acquisition means a moving image!
- Always ensure that the receiving surface of the coil is parallel to the Z axis of the magnet. This guarantees that the transverse component of magnetization is perpendicular to the coil and that maximum signal is induced. Placing the coil at an angle to this axis, or parallel to the X or Y axis, results in a loss of signal (Figure 1.1).

Patient positioning

This contains a description of the correct patient position, placement of the patient within the coil and proper immobilization techniques. Cent-ring and land-marking are described relative to the laser light system as follows (Figure 1.2):

- The **longitudinal alignment light** refers to the light running **parallel** to the bore of the magnet in the **Z axis**.
- The **horizontal alignment light** refers to the light that runs from **left to right** of the bore of the magnet in the **X axis**.
- The **vertical alignment light** refers to the light than runs from the **top to the bottom** of the magnet in the **Y axis**.

It is assumed in Part 2 that the following areas are examined with the patient placed head first in the magnet:

- head and neck (all areas)
- cervical, thoracic and whole spine
- chest (all areas)
- abdomen (for areas superior to the iliac crests)
- shoulders and upper limb (except where specified).

The remaining anatomical regions are examined with the patient placed feet first in the magnet. These are:

- pelvis
- hips
- lower limbs.

Suggested protocol

This is intended as a guideline only. Almost every centre uses different protocols depending on the type of system and radiological preference. However, this section can be helpful for those practitioners scanning without a radiologist, or where the examination is so rare that perhaps neither the radiologist nor the practitioner knows how to proceed. The
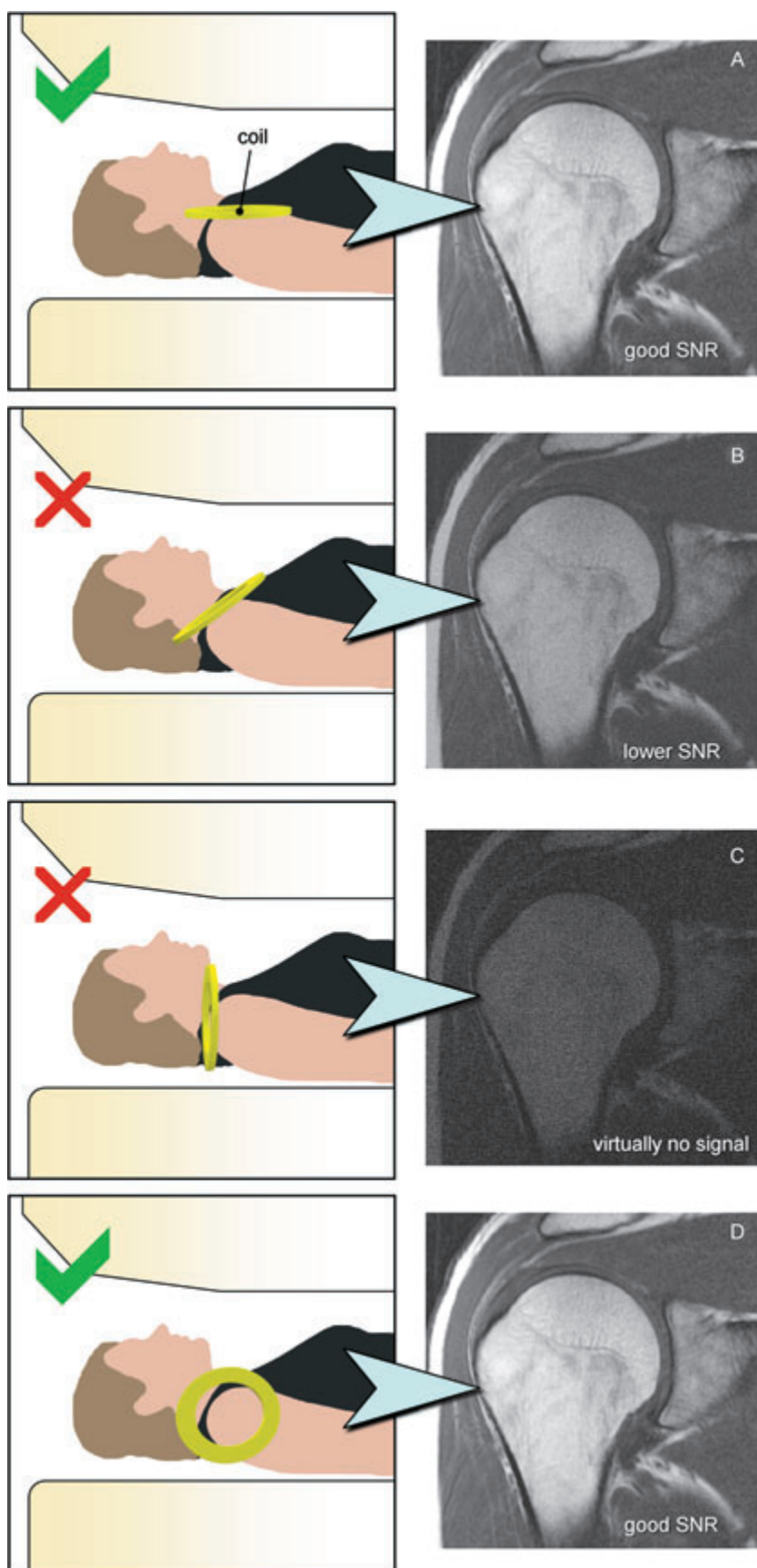
Figure 1.1 Correct placement of a flat surface coil in the bore of the magnet. The surface of the coil (shaded) area must be parallel to the Z axis to receive signal. The coil is therefore positioned so that transverse magnetization created in the X and Y axes is perpendicular to the coil.

Figure 1.2 Positioning of the alignment lights.

protocols given are mainly limited to scan plane, weighting, suggested pulse sequence choices and slice positioning.

It must be stressed that all the protocols listed are only a reflection of the authors' practice and research, and are in no way to be considered the law!

If all your established protocols are satisfactory, this section is included for interest only. If, however, you are unfamiliar with a certain examination, the suggested protocol should be useful.

Occasionally in this section coordinates for slice prescription are given in bold type in millimetres (mm) where explicit prescription can be utilized (mainly for localizers). Graphic prescription coordinates cannot be given as they depend on the exact position of the patient within the magnet and the ROI. The explicit coordinates are always given as follows:

- Left to Right **L to R**
- Inferior to Superior **I to S**
- Posterior to Anterior **P to A**.

In the suggested protocols a certain format is adopted when some parameters remain constant and others change. For example, in the protocol for a coronal spin echo (SE), proton density (PD)/T2 sequence of the brain the text reads.

Coronal SE/FSE PD/T2

As for Axial PD/T2, **except** prescribe slices from the cerebellum to the frontal lobe.

This indicates that the pulse sequence, timing parameters, slice thickness and matrix are the same as the axial except the slices are prescribed through a different area. This format is intended to avoid repetition. In most examinations there is a section reserved for additional sequences. These are extra sequences that we do not regard as routine but may be

1

included in the examination. Of course, some practitioners may regard what we call 'additional' as 'routine', and vice versa.

Image optimization

This section is subdivided into:

- Technical issues
- Artefact problems
- Patient considerations
- Contrast usage.

- **Technical issues:** This includes a discussion of the relationship of SNR, spatial resolution and scan time pertaining to each examination. Suggestions on how to optimize these factors are described (see *Parameters and trade-offs* in Part 1). The correct use of pulse sequences and various imaging options are also discussed (see also *Pulse sequences* in Part 1).
- **Artefact problems:** This contains a description of the common artefacts encountered and ways in which they can be eliminated or reduced (see also *Flow phenomena and artefacts* in Part 1).
- **Patient considerations:** This encompasses the condition of the patient, including symptoms and claustrophobia. Suggestions to overcome these are given (see also *Patient care and safety* in Part 1).
- **Contrast usage:** The reasons for administering contrast in each particular area are discussed. Again, contrast usage varies widely according to radiological preferences. This section is a guideline only (see also *Contrast agents* in Part 1).

Follow this ten point plan for good radiographic practice:

- Review all cases carefully and select appropriate protocols.
- Have flexible protocols that can reflect the needs of each individual clinical case.
- Regularly review your procedures and benchmark them against current best practice.
- Have clear diagnostic goals including the minimum accepted sequences necessary to obtain a useful diagnostic/clinical outcome.
- Regularly review your protocols and procedures.
- Understand the capabilities of your system.
- Recognize your limitations and if necessary refer to another site rather than risking an incomplete or diagnostically unacceptable procedure.
- Educate all levels of staff to new procedures and/or system capabilities.
- Be safety paranoid to ensure your unit does not fall victim to the dreaded MRI incident.
- Most importantly, enjoy your patients and give them the highest standard of care possible.

1

Terms and abbreviations used in Part 2

Wherever possible generic terms have been used to describe pulse sequences and imaging options. Explanations of these can be found in the various sections of Part 1. To avoid ambiguity the specific following terms have been used:

- **Chemical/Spectral presaturation:** fat suppression techniques such as fat saturation (FAT SAT), spectrally selective inversion recovery (SPIR).
- **Gradient moment nulling (GMN):** gradient moment rephasing (GMR) and flow compensation (FC).
- **Oversampling:** no phase wrap, anti-aliasing and anti-foldover.
- **Rectangular/Asymmetric FOV:** rectangular FOV.
- **Respiratory compensation (RC):** phase reordering and respiratory triggering techniques.

Abbreviations are used throughout the book for simplification purposes. A summary of these can be found in the following section *Abbreviations*. In addition a comparison of acronyms used by certain manufacturers to describe pulse sequences and imaging options is given later in Table 3.1 under *Pulse sequences* in Part 1.

Conclusion

To use this book:

- Find the anatomical region required and then locate the specific examination.
- Study the categories under each section. It is possible that all the categories are relevant if the examination is being performed for the first time. However, there may be occasions when only one item is appropriate. For example, there could be a specific artefact that is regularly observed in chest examinations, or image quality is not up to standard on lumbar spines. Under these circumstances read the subsection above entitled *Image optimization*.
- If the terms used, or concepts discussed, in Part 2 are unfamiliar, then turn to Part 1 and read the summaries described there.

Abbreviations

A summary of common abbreviations used in the field of MRI and throughout this book is given below.

A	Anterior
AC	Number of acquisitions
ADC	Apparent diffusion coefficient
ADEM	Acute disseminating encephalomyelitis
ASIS	Anterior superior iliac spine
AVM	Arterio-venous malformation
AVN	Avascular necrosis
BFFE	Balanced fast field echo
BGRE	Balanced gradient echo
BOLD	Blood oxygenation level dependent
CDH	Congenitally dislocated hips
CE-MRA	Contrast enhanced MRA
CNR	Contrast to noise ratio
CNS	Central nervous system
CSE	Conventional spin echo
CSF	Cerebrospinal fluid
CT	Computer tomography
CVA	Cerebral vascular accident
DE prep	Driven equilibrium magnetization preparation
DTI	Diffusion tensor imaging
DWI	Diffusion weighted imaging
ECG	Echocardiogram
EPI	Echo planar imaging
ETL	Echo train length
FA	Fractional anisotropy
FAT SAT	Fat saturation
FC	Flow compensation
FDA	Food and Drugs Administration
FFE	Fast field echo
FIESTA	Free induction echo stimulated acquisition
FID	Free induction decay signal
FISP	Fast imaging with steady precession
FLAIR	Fluid attenuated inversion recovery
FLASH	Fast low angled shot
fMRI	Functional MRI
FOV	Field of view
FSE	Fast spin echo
GFE	Gradient field echo
GMN	Gradient moment nulling
GMR	Gradient moment rephasing
GRASS	Gradient recalled acquisition in the steady state
GRE	Gradient echo

GRE-EPI	Gradient echo EPI
HASTE	Half acquisition single shot turbo SE
I	Inferior
IAM	Internal auditory meatus(i)
IM	Intramuscular
IR	Inversion recovery
IR-FSE	Inversion recovery FSE
IR prep	Inversion recovery magnetization preparation
IV	Intravenous
IVC	Inferior vena cava
L	Left
MP RAGE	Magnetization prepared rapid gradient echo
MR	Magnetic resonance
MRA	Magnetic resonance angiography
MRCP	Magnetic resonance cholangiopancreatography
MRI	Magnetic resonance imaging
MS	Multiple sclerosis
MT	Magnetization transfer
NEX	Number of excitations
NSA	Number of signal averages
P	Posterior
PC	Phase contrast
PC-MRA	Phase contrast MRA
PD	Proton density
Pe	Peripheral
PEAR	Phase encoding artefact reduction
PSIF	Reverse FISP
R	Right
RC	Respiratory compensation
REST	Regional saturation technique
RF	Radio frequency
ROI	Region of interest
RR	R to R interval
S	Superior
SAR	Specific absorption rate
SAT	Saturation
SE	Spin echo
SE-EPI	Spin echo EPI
SNR	Signal to noise ratio
SPAMM	Spatial modulation of magnetization
SPGR	Spoiled GRASS
SPIR	Spectrally selective inversion recovery
SS	Single shot
SS-EPI	Single shot EPI
SSFP	Steady state free precession
SS-FSE	Single shot FSE
STIR	Short TAU inversion recovery
SW	Susceptibility weighted

1

TE	Echo time
TFE	Turbo field echo
TI	Inversion time
TIA	Transient ischaemic attack
TLE	Temporal lobe epilepsy
TMJ	Temporomandibular joint
TOF	Time of flight
TOF-MRA	Time of flight MRA
TR	Repetition time
True FISP	Siemens version of BGE
TSE	Turbo spin echo
VENC	Velocity encoding

Part 1   Theoretical and practical concepts

2

Parameters and trade-offs

Introduction

This section refers mainly to the *Technical issues* subheading discussed under the *Image optimization* heading considered for each examination in Part 2. Only a brief overview is provided here. For a more detailed explanation please refer to Chapter 4 of *MRI in Practice* or an equivalent text.

The main considerations of image quality are:

- signal to noise ratio (SNR)
- contrast to noise ratio (CNR)
- spatial resolution
- scan time.

Each factor is controlled by certain parameters, and each 'trades off' against the other (see later in Table 2.2). This section summarizes the parameters available and the trade-offs involved. Suggested parameters are outlined in Table 2.1, which can be found here and at the beginning of each anatomical region in Part 2. The parameters given should be universally acceptable on most systems. However, weighting parameters in particular are field-strength dependent and therefore some modification may be required if you are operating at extremely low or high field strengths.

Signal to noise ratio (SNR)

The signal to noise ratio (SNR) is defined as the ratio of the amplitude of signal received by the coil to the amplitude of the noise. The signal is the voltage induced in the receiver coil, and the noise is a constant value depending on the area under examination and the background electrical noise of the system. SNR may be increased by using:

- spin echo (SE) and fast spin echo (FSE) pulse sequences
- a long repetition time (TR) and a short echo time (TE)
- a flip angle of 90°
- a well-tuned and correctly sized coil
- a coarse matrix

2

Table 2.1 Summary of parameters. The figures given are general and should be adjusted according to the system used

Spin echo (SE)

short TE	min to 30 ms
long TE	70 ms +
short TR	300−600 ms
long TR	2000 ms +

Fast spin echo (FSE)

short TE	min−20 ms
long TE	90 ms +
short TR	400−600 ms
long TR	4000 ms +
short ETL	2−6
long ETL	16 +

Inversion recovery (IR) T1

short TE	min−20 ms
long TR	3000 ms +
medium TI	200−600 ms
short ETL	2−6

STIR

long TE	60 ms +
long TR	3000 ms +
short TI	100−175 ms
long ETL	12−20

FLAIR

long TE	60 ms +
long TR	3000 ms +
long TI	1700−2200 ms
long ETL	12−20

Coherent GRE

long TE	15 ms +
short TR	≤ 50 ms
flip angle	20°−40°

Incoherent GRE

short TE	min−5 ms
short TR	≤ 50 ms
flip angle	20°−40°

Balanced GRE

TE	minimum
TR	minimum
flip angle	≥ 40°

SSFP

TE	minimum
TR	40−50 ms
flip angle	20°−40°

Slice thickness

2D	thin	2−4 mm
	medium	5−6 mm
	thick	8 mm
3D	thin	≤ 1 mm
	thick	≥ 3 mm

Slice numbers

Volumes	small	≤ 32
	medium	64
	large	≥ 128

Matrix (frequency × phase)

coarse	256 × 128 or 256 × 192
medium	256 × 256 or 512 × 256
fine	512 × 512
very fine	≥ 512 × 512

FOV

small	≤ 18 cm
medium	18−30 cm
large	≥ 30 cm

PC-MRA

2D and 3D	TE	minimum
	TR	25−33 ms
	flip angle	30°
VENC venous	20−40 cm/s	
VENC arterial	60 cm/s	

NEX/NSA

short	≤ 1
medium	2−3
multiple	≥ 4

TOF-MRA

2D	TE	minimum
	TR	28−45 ms
	flip angle	40°−60°
3D	TE	minimum
	TR	25−50 ms
	flip angle	20°−30°

- a large FOV
- thick slices
- the narrowest receive bandwidth available
- as many excitations and signal averages (NEX/NSA) as possible.

In Part 2, the following terms and approximate parameters are suggested when discussing the number of signal averages (NEX/NSA) (see also Table 2.1):

- short NEX/NSA is 1 or less (partial averaging)
- medium NEX/NSA is 2/3
- long or multiple NEX/NSA is 4 or more.

Contrast to noise ratio (CNR)

The contrast to noise ratio (CNR) is defined as the difference in the SNR between two adjacent areas. It is controlled by the same factors that affect the SNR. All examinations should include images that demonstrate a good CNR between pathology and surrounding normal anatomy. In this way pathology is well visualized. The CNR between pathology and other structures can be increased by the following:

- Administration of contrast agents.
- Utilization of T2 weighted sequences.
- Selection of magnetization transfer (MT) sequences.
- Suppression of normal tissues via chemical/spectral presaturation, or sequences that null signal from certain tissues: short TI inversion recovery (STIR), fluid alternated inversion recovery (FLAIR), magnetization-prepared sequences).

Spatial resolution

The spatial resolution is the ability to distinguish between two points as separate and distinct. It is controlled by the voxel size. Spatial resolution may be increased by selecting:

- thin slices
- fine matrices
- a small FOV.

The above criteria assume a square FOV so that if an uneven matrix is used, the pixels are rectangular and therefore resolution is lost. Some systems utilize square pixels so that the phase matrix determines the size of the FOV along the phase encoding axis. In this way resolution is maintained because the pixels are always square. The disadvantage of this system is that the size of the FOV may be inadequate to cover the required anatomy in the phase direction, and SNR is often reduced due to the use

2

of smaller, square pixels. Therefore these systems usually have the option to utilize a square FOV in circumstances where either coverage is required or the SNR is low. In the interests of simplicity, a square FOV is assumed in Part 2, whereby the phase matrix size determines the resolution of the image, not the size of the FOV.

In Part 2 the following terms and approximate parameters are suggested when discussing spatial resolution. The first number quoted is the frequency matrix, the second is the phase matrix (see also Table 2.1):

- a coarse matrix is 256×128 or 256×192
- a medium matrix is 256×256 or 512×256
- a fine matrix is 512×512
- a very fine matrix is any matrix greater than 512×512
- a small FOV is usually less than 18 cm
- a large FOV is more than 30 cm
- on the whole, the FOV should fit the ROI
- a thin slice/gap is 1 mm/1 mm to 4 mm/1.5 mm or less
- a medium slice/gap is 5 mm/2.5 mm to 6 mm/2.5 mm
- a large slice/gap is 8 mm/2 mm or more.

Scan time

The scan time is the time required to complete the acquisition of data. The scan time can be decreased by using:

- a short TR
- a coarse matrix
- the lowest NEX/NSA possible.

In addition to the SNR, CNR, spatial resolution and scan time, the following imaging options are also described under the *Technical issues* subheading mentioned before.

- **Rectangular/asymmetric FOV:** The use of rectangular/asymmetric FOV is often discussed in Part 2. It enables the acquisition of fine matrices but in scan times associated with coarse matrices. It is most useful when anatomy fits into the shape of a rectangle, e.g. sagittal spine. The long axis of the rectangle usually corresponds to the frequency encoding axis and the shorter axis to phase encoding. This is important as certain phase artefacts, such as ghosting and aliasing, occur along the short axis of the rectangle. The dimension of the phase axis is usually expressed as a proportion or percentage of the frequency axis, e.g. 75%. On some systems, rectangular/ asymmetric FOV and oversampling are not compatible. If this is so, signal-producing anatomy existing beyond the FOV along the shorter phase axis is wrapped into the image. This is reduced by increasing the FOV, using spatial presaturation bands to nullify unwanted signal or, if this function is available, by expanding the

short axis dimension to incorporate all signal-producing anatomy (see *Flow phenomena and artefacts*).

- **Volume imaging:** Volume imaging or 3D acquisition collects data from an imaging volume or slab and then applies an extra phase encoding along the slice select axis. In this way, very thin slices with no gap are obtained, and the data set may be viewed in any plane. However the scan time in volume imaging not only depends on the TR, the phase matrix and the number of signal averages/but also on the number of slice locations in the volume. Therefore scan times are considerably longer than in 2D imaging. For this reason fast sequences such as steady state sequences and FSE are commonly used (see *Pulse sequences*). To maintain resolution in all viewing planes, the voxels should be isotropic, i.e. they have the same dimensions in all three planes. This is achieved by selecting an even matrix and a slice thickness equal to, or less than, the pixel size. For example, if a matrix size of 256×256 is chosen and the FOV is 25 cm, a slice thickness of 1 mm achieves the required resolution. With a larger FOV a slightly thicker slice can be used. The penalty of isotropic voxels, however, is a reduction in SNR due to the use of smaller, square voxels. In addition more slices may be required to cover the imaging volume resulting in long scan times. This is compensated for to some degree by the fact that, as there are no gaps, a greater volume of tissue is excited and therefore overall signal return is greater. Nevertheless when volume imaging is employed, the need for resolution in all planes must be weighed against some loss of SNR and longer scan times. As the slices are not individually excited as in conventional acquisitions, but are located by an extra phase encoding gradient, aliasing along the slice select axis occurs. This originates from anatomy that lies within the coil (and therefore produces signal), and exists outside the volume along the slice encoding axis. It manifests itself by the first and last few slices of the imaging volume wrapping into each other and potentially obscuring important anatomy. To avoid this always over-prescribe the volume slab so that the ROI, and some anatomy on either side of it, are included. In this way any slice wrap does not interfere with the ROI (see *Flow phenomena and artefacts*). Volume imaging is commonly used in the brain and to examine joint anatomy, especially when very thin slices are required. In Part 2 the following terms and approximate parameters are suggested when discussing volume imaging (see also Table 2.1):

  - A thin slice is 1 mm or less.
  - A thick slice is more than 3 mm.
  - A small number of slice locations is approximately 32.
  - A medium number of slice locations is approximately 64.
  - A large number of slice locations is approximately 128 or more.

The following combination of parameters usually yields the optimum SNR and scan time in volume imaging, although this depends on the coil

2

type, the proton density of the area under examination, the slice thickness, and the field strength:

- 32 locations use 2 or more NEX/NSA
- 64 locations use 1 NEX/NSA
- 128 locations use less than 1 NEX/NSA.

Decision strategies

To optimize image quality the data should have a high SNR, good resolution and be acquired in a short scan time. This is usually impossible. however, as the factors that must be increased to improve SNR may have to be decreased to gain spatial resolution. An example of this is matrix selection. A coarse matrix is required to obtain large voxels and therefore a high SNR. However, a fine matrix with small voxels and low SNR is not only necessary to maintain good spatial resolution, but also increases the scan time as more phase encodings are performed. The operator must decide which factor (either SNR, resolution or scan time) is the most important and optimize this. One or both of the other two may have to be sacrificed accordingly.

When discussing these issues in Part 2 the importance of good SNR over the other factors is emphasized, as in our view there is little point in having an image with good resolution if the SNR is poor. The selection of an appropriately sized and tuned coil is also important, together with the proton density of the area under examination. For example, when examining the chest, which has a low SNR, the parameters selected must optimize the SNR as much as possible, and resolution and scan time are sacrificed. The importance of limiting the scan time for patient toleration is also discussed in Part 2. If the scan time is lengthy, all patients will eventually become uncomfortable and move. The resultant motion artefact degrades any image regardless of its SNR or resolution characteristics. Therefore it is important to minimize scan times to acceptable levels. If patients are in pain or uncooperative, this strategy is even more important.

Conclusion

The variety of parameters used in MRI is often bewildering, but their importance is undisputed, especially in determining image quality. A good working knowledge of these parameters and how they interrelate is necessary to ensure an optimum examination. Table 2.2 summarizes these trade-offs. The choice of pulse sequence is also important in determining image contrast, and these are outlined in the next section.

Table 2.2 Parameters and their trade-offs

Parameter	Advantages	Disadvantages
TR increased	Increased SNR Increased number of slices per acquisition	Increased scan time Decreased T1 weighting
TR decreased	Decreased scan time Increased T1 weighting	Decreased SNR Decreased number of slices per acquisition
TE increased	Increased T2 weighting	Decreased SNR
TE decreased	Increased SNR	Decreased T2 weighting
NEX increased	Increased SNR of all tissues Reduced flow artefact due to signal averaging	Direct proportional increase in scan time
NEX decreased	Direct proportional decrease in scan time	Decreased SNR in all tissues Increased flow artefact due to less signal averaging
Slice thickness increased	Increased SNR in all tissues Increased coverage of anatomy	Decreased spatial resolution and partial voluming in slice select direction
Slice thickness decreased	Increased spatial resolution and reduced partial voluming in slice select direction	Decreased SNR in all tissues Decreased coverage of anatomy
FOV increased	Increased SNR Increased coverage of anatomy	Decreased spatial resolution Decreased likelihood of aliasing
FOV decreased	Decreased SNR in all tissues Decreased coverage of anatomy	Increased spatial resolution Increased likelihood of aliasing
Matrix increased	Increased spatial resolution	Decreased SNR if pixel size decreases. If pixel size remains the same, SNR will increase because more phase encodings are performed. Increased scan time
Matrix decreased	Increased SNR in all tissues if pixel size increases. If pixel size remains the same, SNR decreases as fewer phase encodings are performed. Decreased scan time	Decreased spatial resolution
Receive bandwidth increased	Decrease of minimum TE Decrease in chemical shift	Decreased SNR
Receive bandwidth decreased	Increased SNR	Increase in minimum TE Increase in chemical shift

2

3

Pulse sequences

Introduction

This section refers mainly to the *Suggested protocol* heading considered for each examination in Part 2, although pulse sequences are sometimes mentioned under the *Technical issues* subheading of *Image optimization*. A summary of the mechanisms and uses of the most commonly used pulse sequences are described. All pulse sequences are described using their generic name. Table 3.1 provides a comparison of the acronyms used by the main manufacturers to describe their pulse sequences and imaging options. The parameters given in Table 2.1 should be universally acceptable on most systems. However, weighting parameters in particular are field-strength dependent and therefore some modification may be required if you are operating at extremely low or high field strengths. Only a brief overview is provided here. For a more detailed explanation please refer to Chapters 2 and 5 of *MRI in Practice* or an equivalent text.

Spin echo (SE)

A spin echo (SE) pulse sequence (also known as conventional spin echo (CSE)) usually uses a 90° excitation pulse followed by a 180° rephasing pulse to produce a spin echo. Some SE sequences use a variable flip angle, but traditionally the excitation pulse has a magnitude of 90°. This amplitude of the flip angle is consistently assumed in the protocols. SE sequences can be used to generate one or several spin echoes. One echo is usually used for T1 weighting while two echoes are used for proton density (PD) and T2 weighting. SE pulse sequences are the most commonly implemented sequences as they produce optimum SNR and CNR.

For **T1 weighting** in SE use:

short TE	min–20 ms
short TR	300–600 ms

For **PD/T2 weighting** in SE use:

short TE	20 ms (first echo PD)
long TE	70 ms (second echo T2)
long TR	2000 ms

Table 3.1 Comparison of manufacturer acronyms (see *How to use this book* for abbreviations)

Pulse sequence/Imaging option	General Electric	Philips	Siemens
Spin echo	Spin echo	Spin echo	Spin echo
Fast spin echo	FSE	TSE	TSE
Coherent gradient echo	GRASS	FFE	FISP
Balanced gradient echo	FIESTA	BFFE	True FISP
Incoherent gradient echo	SPGR	T1 FFE	FLASH
Steady state free precession	SSFP	T2 FFE	PSIF
Inversion recovery (IR)	IR	IR	IR
Short TI inversion recovery	STIR	STIR	STIR
Fluid attenuated inversion recovery	FLAIR	FLAIR	FLAIR
Presaturation	SAT	REST	SAT
Gradient moment nulling	FC	FC	GMR
Respiratory compensation	RC	PEAR	RC
Signal averaging	NEX	NSA	AC
Partial averaging	Fractional NEX	Half scan	Half Fourier
Oversampling	No phase wrap	Fold over suppression	Oversampling
Rectangular/asymmetric FOV	Rectangular FOV	Rectangular FOV	Undersampling FOV

Fast spin echo (FSE) or turbo spin echo (TSE)

Fast spin echo (FSE) uses a 90° flip angle followed by several 180° rephasing pulses to produce several spin echoes in a given TR. Each echo is phase encoded with a different amplitude of gradient slope, so that data from each echo are collected and stored in a different line of K space. In this way more than one line of K space is filled per TR, and the scan time is reduced accordingly. The echo train length (ETL) (also known as the turbo factor) refers to the number of 180° rephasing pulses and therefore echoes that correspond to the number of lines of K space filled per TR. The longer the ETL the shorter the scan time as more lines of K space are filled per TR.

FSE can be used to produce either one or two echoes as in SE. The echo train may be split so that data are collected from the first half of the echo train to acquire the first echo, and from the latter half to acquire the second echo. This strategy is commonly used to produce PD and T2 images that demonstrate similar weighting to SE. However, T2 images can be acquired without a PD image. A T2 image alone, rather than a dual echo, is often acquired in Part 2. It is of course perfectly justified to use a dual echo sequence if this is required. For more information see *Technical Issues* in *Brain* in Part 2.

FSE sequences have been further modified to include 3D acquisitions and single-shot techniques. Single shot FSE (SS-FSE), which is also termed

HASTE (half acquisition single shot turbo echo), combines long ETLs which fill all of K space in one shot with half Fourier acquisition techniques that acquire only half of K space and then transpose data into the other half. This technique allows very rapid acquisitions, which enables multiple slice breath-hold and real-time imaging.

Some contrast characteristics of FSE differ from conventional SE. Fat remains bright on T2 weighted images and fat suppression techniques may be needed to compensate for this. The multiple 180° RF pulses used in FSE sequences cause lengthening of the T2 decay time of fat so that the signal intensity of fat on T2 weighted FSE images is higher than in SE. This sometimes makes the detection of marrow abnormalities difficult. Therefore when imaging the vertebral bodies for metastatic disease, a STIR sequence should be utilized. Muscle can appear darker than usual especially on the T2 weighted images. This is again due to the multiple 180° pulses causing a MT effect.

In addition, certain artefacts may be prominent in FSE sequences. Image blurring is often a problem in long ETL sequences. This occurs because each line of K space contains data from echoes with a different TE. In long ETL sequences, the very late echoes have a low signal amplitude and, as the outer lines of K space are filled with data from these echoes, there are insufficient data to provide adequate resolution. Image blurring is most commonly seen at the edges of tissues with different T2 decay times. It may be reduced by decreasing the size of the FOV in the phase direction (depending on how the manufacturer implements a rapid FSE sequence) or by selecting a broad receive bandwidth. However, while the latter does improve overall image quality by reducing blurring, it also reduces the SNR. Lastly, FSE is not always compatible with options such as phase reordered respiratory compensation (RC) and therefore conventional SE or breath-hold sequences are often the sequence of choice when respiratory artefact is likely to be troublesome.

For **T1 weighting** in FSE use:

short TE	min–20 ms
short TR	400–600 ms
short ETL	2–6

For **T2 weighting** in FSE use:

long TE	≥ 90 ms
long TR	≥ 4000 ms
long ETL	≥ 16

For **PD/T2 weighting** in FSE use:

short TE	min–20 ms (first echo PD)
long TE	≥ 90 ms (second echo T2)
long TR	≥ 4000 ms
medium ETL	8–12 (split 4 and 4 or 6 and 6)

Inversion recovery (IR/IR-FSE)

Inversion recovery (IR) pulse sequences begin with a 180° pulse that inverts the net magnetization vector into full saturation. When the inverting pulse is removed, the magnetization begins to recover and return

towards B_0. After a specific time TI (inversion time), a 90° excitation pulse is applied which transfers the proportion of magnetization that has recovered to B_0 into the transverse plane. This transverse magnetization is then rephased by a 180° rephasing pulse to produce an echo. In IR-FSE several 180° rephasing pulses are applied as in FSE, so that more than one line of K space can be filled per TR, so reducing the scan times.

Conventional IR is most commonly used to produce heavily T1 weighted images. However, it and IR-FSE may also be implemented to eliminate the signal from certain tissues by applying the 90° excitation pulse when the magnetization in that tissue has recovered into the transverse plane and therefore has no longitudinal component. In this way the signal from the tissue is nulled by the excitation pulse. There are two main uses of this technique. Short TI inversion recovery (STIR) uses a short TI that corresponds to the null point of fat so that the excitation pulse specifically nulls the signal from fat. In Part 2 STIR is used as a fat suppression technique in conjunction with a FSE sequence to produce T2 weighting by using long TEs and ETLs. Fluid attenuated inversion recovery (FLAIR) utilizes a long TI corresponding to the null point of cerebrospinal fluid (CSF) so that the excitation pulse specifically nulls the signal from CSF. Again long TEs and ETLs that enhance T2 weighting are commonly used to enhance the signal from pathology especially periventricular lesions.

For **T1 weighting** in IR use:

short TE	min–20 ms
long TR	≥ 2200 ms
medium TI	200–600 ms (depending on the field strength)

For **STIR** use:

TE	60 ms
TR	6000 ms
ETL	16
short TI	100–175 ms

For **FLAIR** use:

TE	60 ms
TR	6000–10 000 ms
ETL	16
long TI	1700–2200 ms

In all IR sequences the TI is field-strength dependent. In FLAIR sequences combined with long ETL FSE, if the TR is not long enough to allow full recovery of z magnetization after the last echo in the train has been collected, a shorter TI than usual may be required to null the CSF signal adequately. This is because if only partial z magnetization has recovered at the end of the TR period, this is converted into only partial –z magnetization after inversion and therefore the magnetization in CSF does not take as long to reach its null point.

Coherent gradient echo (GRE) (T2*)

Coherent gradient echo (GRE) pulse sequences use a variable flip angle followed by gradient rephasing to produce a gradient echo. This sequence

3

utilizes the steady state so that the transverse component of magnetization is allowed to build up over successive repetition times. This is achieved by a reversal of the phase encoding gradient prior to each repetition that rephases this transverse magnetization. In this way the coherence of the transverse magnetization is maintained, so that mainly signal from tissues with a high water content and a long T2 is present in the image. They are often said to demonstrate an angiographic, myelographic or arthrographic effect as blood, CSF and joint fluid are bright. As the TR is short, these sequences are mainly used for breath-holding or in a volume acquisition. The TR can be lengthened, however, to achieve multi-slice acquisitions demonstrating excellent contrast. This strategy is common in spinal and joint imaging.

Faster versions of this sequence are available enabling multiple slice breath-hold, dynamic and real-time imaging. Scan times are reduced by a combination of partial RF pulses, partial Fourier acquisitions and centric K space filling. Owing to the inherent lack of contrast in this sequence, magnetization preparation pulses are sometimes used that either null the signal from certain tissues, thereby increasing the CNR between them and the surrounding structures, or increase overall T2 contrast.

For **T2* coherent GRE** use:

short TR	≤ 50 ms (300–600 ms in multi-slice acquisitions)
long TE	15 ms
medium flip angles	30°–45°

Balanced gradient echo (GRE) (T2)*

Balanced GRE (BGRE) is a steady state sequence that uses a very short TR for rapid acquisition times and large flip angles to increase SNR. This combination would normally result in saturation or T1 weighting. Therefore some manufacturers alternate the phase of each excitation pulse so that transverse magnetization is not additive, thereby allowing for large flip angle/short TR combinations without saturation. The short TR values reduce the time for flow effects, and balanced gradients that use zero time-integrated areas in all three axes are also used to reduce flow artefact. This is a 'pure' steady state sequence as signal is obtained from both the longitudinal and transverse steady-state. These characteristics, along with ultra-short TR and TE times, result in images that are weighted for the ratio of T2 / T1. Spins with a high T2 / T1 ratio are bright; those with a low T2 / T1 ratio are dark. The two most common substances with a high T2 / T1 ratio are blood and CSF.

For **T2* BGRE**

short TR	8 ms
short TE	4 ms
large flip angle	≥ 40°

3

Incoherent (spoiled) gradient echo (GRE) (T1/PD)

Incoherent (spoiled) GRE sequences also use a variable flip angle and gradient rephasing resulting in a gradient echo. They are commonly used in the steady state so that residual magnetization builds up in the transverse plane. However, these sequences spoil this magnetization with phase shifted RF pulses that do not allow the residual transverse magnetization to be received. T2* weighting does not, therefore, dominate image contrast to as great an extent as coherent GRE pulse sequences, and the images are mainly T1/PD weighted. Owing to the short TR, these sequences can be used for breath-holding, dynamic imaging, and in cine and volume acquisitions. As they are mainly T1/PD weighted, they are very effective in conjunction with contrast enhancement and to demonstrate anatomy.

As with coherent GRE there is a faster version of this sequence enabling multiple slice breath-hold, dynamic imaging after contrast and real-time imaging. Scan times are reduced by a combination of partial RF pulses, partial Fourier acquisitions and centric K space filling. Owing to the inherent lack of contrast in this sequence, magnetization preparation pulses are sometimes used that either null the signal from certain tissues, thereby increasing the CNR between them and surrounding structures, or increase the overall T2 contrast.

For **T1/PD incoherent (spoiled) GRE** use:

short TR	≤ 50 ms
short TE	min–5 ms
medium flip angle	30°–45°

Steady state free precession (T2)

This is a steady state sequence that uses medium flip angles and a short TR to maintain the steady state so that residual magnetization builds up in the transverse plane. These sequences generate contrast by sampling this transverse magnetization, which is mainly T2 weighted. The T2 weighted echo is repositioned by a gradient so that the TE is longer than the TR. Hence true T2 weighting can be achieved in conjunction with a short TR. The actual TE selected at the console is 2 × the TR minus the time between the echo and the next RF pulse (usually called, very confusingly, the TE). Therefore the shorter the TE selected at the console, the longer the actual TE and hence the greater the T2 weighting of the image.

For **T2 SSFP** use:

short TR	≤ 50 ms
short TE	shortest
medium flip angle	30°–45°

3

Echo planar imaging (EPI)

Echo planar imaging (EPI) sequences fill all of K space in one repetition (called single shot) or multiple repetitions (called multi-shot) by using very long echo trains. Echoes are produced by alternating the frequency encoding gradient and therefore the echoes that fill K space are gradient echoes (if the echoes are spin echoes resulting from repeated application of a 180° rephasing pulse the sequence is called FSE). EPI sequences are given terms depending on what precedes the EPI filling of K space. If the sequence begins with a 90°/180° combination this is called SE-EPI. If the sequence begins with a 180°/90°/180° combination this is called IR-EPI. If the sequence begins with a single RF excitation pulse of any flip angle (i.e. there is no 180° RF rephasing pulse) it is called a GE-EPI.

If all of K space is filled in one go, this is termed single shot EPI (SS-EPI). SS-EPI produces images much more rapidly than SS-FSE as it uses a train of gradient echoes rather than spin echoes and can therefore fill K space in a fraction of a second. However, SS-EPI sequences are very prone to artefacts such as chemical shift, distortion and blurring. These artefacts increase relative to the echo spacing and therefore the time of the echo train. For this reason EPI sequences are often used in multi-shot mode where a quarter or a half of K space is filled per TR period thereby reducing the time of the echo train. This can also be minimized by implementing any, or all, of the following:

- increasing the FOV
- increasing the receive bandwidth
- reducing the frequency encoding matrix
- reducing the phase FOV.

EPI, BGRE and the fast versions of both coherent and incoherent (spoiled) GRE sequences currently represent the fastest acquisition modes in MRI. Real-time, dynamic and functional studies are possible using this technique. Some of these are discussed in Part 2 and are therefore summarized here.

- **Real-time imaging:** Very fast sequences, such as EPI, permit real-time imaging of moving structures. This is proving to be very useful in interventional procedures where a biopsy needle, laser probe or other instrument can be visualized in real-time. Biopsies, thermal ablations of tumours, angioplasties, endoscopies and limited-field surgical operations are the most promising applications of this technique (see also *Dynamic imaging* below).
- **Dynamic imaging:** Dynamic imaging refers to the rapid acquisition of images either after contrast enhancement, or to observe movement. It may be utilized to visualize the motion of a joint (e.g. a knee), or a structure such as the cervical spine or pelvic floor. Single images may be obtained using GRE or EPI sequences in various degrees of motion. Alternatively multiple slices can be acquired either to cover more anatomy, or to visualize the structure in many

3

positions during data acquisition. When used with EPI, acquisitions in the order of 20 images per second are possible and therefore these techniques are termed real-time. If used in conjunction with GRE sequences, however, data acquisition is much slower and therefore these techniques are termed quasi real-time. Depending on the temporal resolution of the structure under examination, quasi real-time techniques may not always provide an accurate representation of motion. Used in conjunction with contrast enhancement, dynamic imaging visualizes the speed of uptake of contrast, which may be necessary to determine the nature of a lesion. This is termed perfusion imaging (see also *Brain* in Part 2). It can be used in many areas including the brain, pancreas, liver and prostate. One of the most important applications of dynamic imaging is in the breast where contrast enhancement is useful to characterize a lesion. Benign lesions take longer to enhance than malignant lesions, and scar tissue may not enhance at all. As gadolinium is given, a T1 sequence is required and, due to the dynamic nature of the series, the acquisition times must be as short as possible. Incoherent (spoiled) GRE or FSE sequences are therefore ideal for this type of examination. The entire breast, rather than only a few slices through a lesion, can be demonstrated (some systems now have ultrafast volume acquisition available). This method is obviously important if multi-focal disease is suspected. Tissue characterization by measuring uptake of contrast is also a useful technique in the prostate.

- **Functional imaging (fMRI):** Functional imaging (fMRI) is a rapid technique that acquires images of the brain during activity or stimulus and at rest. The two sets of images are then subtracted demonstrating functional brain activity as a result of increased blood flow to the activated cortex. The mechanism responsible for contrast in functional imaging is termed BOLD (blood oxygenation level dependent), which exploits the differences in magnetic susceptibility between oxy- and deoxyhaemoglobin. This results in an increased signal intensity in activated areas of the cortex that have lower levels of deoxyhaemoglobin than inactivated areas. The high signal is then overlaid on to anatomical images. Functional MRI is useful to evaluate brain activity in a whole range of disorders including epilepsy, stroke and behavioural problems.
- **Diffusion weighted imaging (DWI):** Diffusion weighted imaging (DWI) demonstrates areas with restricted diffusion of extracellular water such as infarcted tissue. In normal tissue, extracellular water diffuses randomly whereas in ischaemic tissue, cells swell and absorb water thereby reducing average diffusion. In DWI the sequence can be sensitized to diffusion by applying equal gradients on each side of a 180° RF pulse. Hence diffusion weighted images are most effectively acquired using SE type sequences such as SE or SE-EPI. These gradient pulses are designed to cancel out the phase shift of stationary spins whilst moving spins experience a phase

3

shift. Therefore signal attenuation occurs in normal tissue with random motion and high signal appears in tissues with restricted diffusion. The amount of attenuation depends on the amplitude of the gradients which is altered by selection of a b-value (expressed as s/mm^2). Gradient pulses can be applied along the X, Y and Z axes to determine the axis of restricted diffusion. The term isotropic diffusion is used to describe diffusion gradients applied in all three axes. DWI is mainly useful in the brain to differentiate salvageable and non-salvageable tissue after stroke. It is also useful in the liver, prostate, spine and bone marrow.

- **Perfusion imaging:** Perfusion imaging refers to the microscopic changes in perfusion when gadolinium first passes through the capillary bed. Mainly used in the brain to assess perfusion kinetics, the MR sequence is sensitized to the very transient changes in T2* as a bolus of contrast first passes through the capillary bed of the area under investigation. Therefore GRE sequences are always used and typically SS-GE-EPI is common. Images are acquired very rapidly before, during and after an injection of a small bolus of contrast in the ante-cubital fossa. Images are then post-processed and perfusion graph and haemodynamic images are produced.

Magnetic resonance angiography (MRA)

The principle of magnetic resonance angiography (MRA) is to acquire images where the signal returned from flowing nuclei is high, and the signal from stationary nuclei is low. In this way contrast between vessels and background tissue is achieved. There are several techniques available to obtain this contrast. Black-blood imaging combines SE or FSE sequences with spatial presaturation pulses to produce images in which flowing vessels appear black. High signal seen in this type of sequence may indicate stenosis or occlusion of the vessel (see *Flow phenomena and artefacts*). Bright-blood imaging combines GRE sequences with GMN to produce images where flowing vessels are bright. A signal void seen in this type of sequence may indicate either a stenosis or occlusion of the vessel (see *Flow phenomena and artefacts*).

There are additional techniques designed especially for angiography. Both allow for data acquisition in either sequential (2D) or volume (3D) mode. Each has its own advantages and disadvantages and therefore each is used for different purposes. The two types of MRA are summarized below. These are time of flight (TOF) and phase contrast (PC).

- **Time of flight (TOF):** This usually uses an incoherent (spoiled) GRE sequence in conjunction with TR and flip angle combinations that saturate background tissue, but allow moving spins to enter the slice/volume fresh and therefore return a high signal. Spatial presaturation pulses placed between the origin of flow and the FOV saturate moving spins entering the FOV, thereby improving visualization of either arterial or venous circulation. These pulses are often concatenated in 2D acquisitions so that the spatial

3

presaturation pulse is applied around each slice in the stack, as opposed to the whole set of slices. This strategy improves the efficiency of presaturation. Unwanted signal is sometimes generated by tissues that have very short T1 recovery times (such as fat), as they recover some of their longitudinal magnetization between each RF pulse and therefore produce signal. Spectral/chemical presaturation pulses, imaging with a TE that collects the echo when fat and water are out of phase with each other, and utilizing magnetization transfer (MT) contrast, commonly reduce this problem. In volume imaging, flowing spins often become saturated by the RF pulses, thereby reducing their signal. This problem can be minimized by the implementation of ramped flip angles, which initially use small flip angles, and then gradually increase them incrementally during data acquisition. In this way the saturation of flowing nuclei is delayed, therefore maintaining vessel signal. In 2D acquisitions, however, TOF-MRA provides good vessel contrast as nuclei are not usually present in the slice long enough to become saturated. Common applications are to demonstrate venous and arterial flow in the head, neck and peripheral vessels.

For **2D TOF-MRA** use:

TR	28–45 ms
Flip angle	40°–60°
TE	minimum

For **3D TOF-MRA** use:

TR	25–50 ms
Flip angle	20°–30°
TE	minimum

Phase contrast (PC): This usually uses a coherent GRE sequence acquired both with, and without, a bipolar gradient pulse. The phase acquired by flowing spins as a result of the application of the bipolar gradient is used to produce images based on subtraction. Sensitivity to flow velocity is controlled by a parameter called velocity encoding or VENC, which can be applied in one, or all three orthogonal planes. PC-MRA provides excellent background suppression and avoids intra-slice/slab flow saturation. However, the scan times associated with PC-MRA are often very long as the scan time is dependent not only on the TR, matrix size and NEX/NSA, but also on the number of flow encoded axes. Common applications are to demonstrate arterial flow in the head and major vessels.

For **2D and 3D PC MRA** use:

TR	25–33 ms
Flip angle	20°
TE	minimum
VENC	20–40 cm/s for venous flow, increase up to 60 cm/s for arterial flow

- **Contrast enhanced MRA (CE-MRA):** This is a technique that involves injecting a small amount of gadolinium or a similar agent into the ante-cubital fossa and scanning an area of the patient to

3

visualize the contrast enhanced vessels. Usually the timing is such that the arterial supply is seen but scans may be delayed slightly to visualize venous structures. In arterial imaging, the sequences used must be rapid ones to enable accurate visualization in the arterial phase. Typically T1 weighted GRE sequences are used as they provide the optimum combination of speed, image quality and contrast. If the ROI is in the chest and abdomen, the patient is usually required to hold his or her breath during acquisition. CE-MRA has an advantage over conventional MRA techniques in that vessel visualization is not as susceptible to flow and directional effects and is thought to be more accurate. However it does involve an injection of contrast media. Renal, carotid and peripheral arteries are commonly examined with this technique.

● **Magnetization transfer (MT) contrast:** Magnetization transfer (MT) is a technique that is commonly used to suppress background tissue thereby enhancing the conspicuity of vessels and certain disease processes. Its function is based on the relaxation differences

Table 3.2 Summary of the contrast characteristics of pathology and normal anatomy

	T1	T2
High signal	Fat Haemangioma Intra-osseous lipoma Radiation change Degenerative fatty deposition Methaemoglobin Cysts with proteinaceous fluid Paramagnetic contrast agents Slow-flowing blood	CSF Synovial fluid Haemangioma Infection Inflammation Oedema Some tumours Haemorrhage Slow-flowing blood Cysts
Low signal	Cortical bone AVN Infarction Infection Tumours Sclerosis Cysts Calcification	Cortical bone Bone islands Deoxyhaemoglobin Haemosiderin Calcification T2 paramagnetic agents
	T1 and T2	
No signal	Air Fast-flowing blood Ligaments Tendons Cortical bone Scar tissue Calcification	

between water protons in different environments. Water protons broadly fall into two categories: those that are free, and those that are bound to surrounding immobile macromolecules. MT involves the exchange of magnetization between the free and bound water protons. Presaturation off-resonant pulses applied just before the RF excitation pulse saturate the bound protons and promote an exchange of some of this saturated magnetization on to the free protons. This pulse is designed to excite hydrogen protons in macromolecules such as proteins. These relatively large molecules have a very short T2 and usually do not contribute to the MR image. With the MT pulse, however, some of these spins transfer their magnetization to the more mobile water spins. This results in a reduced signal return from the free protons. For example, grey and white matter loses 30–40% of its signal when an MT pulse sequence is utilized. The common uses of MT are to increase the conspicuity of certain disease processes such as multiple sclerosis, haemorrhage and AIDS, and to improve vessel contrast in TOF-MRA images by suppressing background tissue.

Conclusion

The choice of pulse sequence is usually the first decision made by either the radiologist or practitioner as it determines the weighting and contrast characteristics of the image. Table 3.2 summarizes the contrast characteristics of pathology and normal anatomy. Careful consideration of the image quality and the required scan time parameters is also necessary to achieve the optimum examination. The flow and artefact phenomena common to the area under examination must also be taken into account, as some compensation techniques may compromise the pulse sequence chosen. These phenomena are discussed in the next section.

4

Flow phenomena and artefacts

Flow phenomena

Introduction

This section refers mainly to the *Artefact problems* subheading discussed under the *Image optimization* heading considered for each examination in Part 2. The most common flow phenomena are summarized in Table 4.1. Only a brief overview is provided here. For a more detailed explanation please refer to Chapter 6 of *MRI in Practice* or an equivalent text.

The most common types of flow phenomena are:

- time of flight (TOF) (not to be confused with TOF MRA)
- entry slice phenomenon
- intra-voxel dephasing.

Table 4.1 Artefacts and their remedies

Artefact	Remedy	Penalty of remedy
Truncation	Increase phase encodings	Increases scan time
	Use more than one NEX/NSA	Increases scan time
Phase mismapping	Respiratory compensation	May lose slices
	Gating	TR variable
	Presaturation	May lose slices
	Gradient moment nulling	Increases minimum TE
	Immobilize patient	None
	Use antispasmodic agent	Costly, invasive
	Sedation	Invasive, requires monitoring
Chemical shift	Increase bandwidth	Decreases TE
	Reduce FOV	Reduces SNR
	Use chemical saturation	Reduces SNR
Chemical misregistration	Set TE at multiple of periodicity	None
Aliasing	Over-sampling (frequency)	None
	Over-sampling (phase)	None or increase in scan time depending on system
	Enlarge FOV	Reduces resolution
Zipper	Call engineer	Irate engineer!
Magnetic susceptibility	Use spin echo	Not flow sensitive
	Remove metal where possible	None
Shading	Load coil properly	None
Cross talk	None	None
Cross excitation	Interleaving of slice acquisition	Doubles the scan time
	Squaring off of RF pulses	Reduces SNR

4

4

Time of flight (TOF)

Time of flight (TOF) phenomenon occurs because nuclei that move through the slice may receive only one of the RF pulses applied. In GRE sequences the gradient rephasing is not slice selective, so nuclei produce signal as long as they have been excited at some point and are rephased by the gradient. In a SE sequence, a nucleus may receive the excitation pulse but then exit the slice before the 180° rephasing pulse can be applied. Conversely, it may not be present in the slice when the excitation pulse is applied, and then enter the slice to receive only the 180° pulse. Under these circumstances the nucleus does not produce a signal. In SE sequences, TOF effects cause either a signal loss or signal enhancement from flowing nuclei, and they are compensated for by using presaturation pulses placed between the origin of the flow and the FOV.

Entry slice phenomenon

This phenomenon depends on the excitation history of nuclei flowing within a vessel, and is largely controlled by the direction of flow relative to slice excitation. Nuclei that flow in the same direction as slice excitation receive several RF excitation pulses and quickly become saturated. Nuclei that flow in the opposite direction to the slice excitation do not experience repeated RF excitation pulses, as they are always entering the selected slice 'fresh'. They are, therefore, not saturated as quickly as nuclei flowing in the same direction as slice excitation. These phenomena result in a difference in signal between arteries and veins where flow is perpendicular to the slice plane, and is most prominent in the first and last slices of the imaging stack. Entry slice phenomenon is compensated for by using presaturation pulses placed between the origin of the flow and the FOV.

Intra-voxel dephasing

This is caused by the presence of gradients that either accelerate or decelerate flowing nuclei as they move from areas of differing field strength along the gradient. As a result of this acceleration or deceleration, the flowing nuclei either gain or lose phase relative to their stationary counterparts. This phase difference between stationary and flowing nuclei in the same voxel causes dephasing and a signal loss. Intra-voxel dephasing is compensated for by using gradient moment nulling (GMN).

Flow artefact remedies

The two main remedies of flow-related artefacts are:

- spatial presaturation pulses
- gradient moment nulling (GMN).

Spatial presaturation: nullifies signal from nuclei that produce unwanted signal or artefact by applying a 90° RF pulse to selected tissue before the pulse sequence begins. Therefore, the magnetic moments of these nuclei are inverted to 180° by the excitation pulse and return no signal. Presaturation pulses may also be delivered at the specific precessional frequency of either fat or water to nullify signal from these types of tissue. This technique, which is called chemical/spectral presaturation, either utilizes a 90° saturation pulse as described above, or the pulse has a greater magnitude and inverts the magnetization in the tissue as in inversion recovery pulse sequences (see *Pulse sequences*). Chemical presaturation can be used to distinguish between fat and enhancing pathology in T1 weighted sequences and in FSE T2 weighted sequences where fat and pathology are often isointense.

Spatial presaturation:

- produces low signal from flowing nuclei;
- reduces motion and aliasing if bands are placed over signal-producing anatomy;
- increases the specific absorption rate (SAR) and may reduce the slice number available per TR;
- mainly reduces time of flight and entry slice phenomena.

Gradient moment nulling (GMN): utilizes extra gradients to rephase the magnetic moments of flowing nuclei so that they have a similar phase to their stationary counterparts.

GMN:

- produces high signal from flowing nuclei;
- increases the minimum TE and may reduce the slice number available;
- mainly reduces intra-voxel dephasing.

Both GMN and spatial presaturation decrease flow artefact seen on an image, but are also valuable in reducing phase mismapping and motion artefact.

4

Artefacts

Introduction

This section also refers mainly to the *Artefact problems* subheading discussed under the *Image optimization* heading considered for each examination in Part 2. The most common artefacts are summarized in Table 4.1. Only a brief overview is provided here. For a more detailed explanation please refer to Chapter 7 of *MRI in Practice* or an equivalent text.

The most common types of artefact seen in MR images are:

- phase mismapping (motion)
- aliasing (wrap)
- chemical shift
- chemical misregistration
- truncation
- magnetic susceptibility.

Phase mismapping

Phase mismapping or ghosting is caused by anatomy moving between each application of the phase encoding gradient, and by motion along the phase encoding gradient during the acquisition of data. Pulsatile motion of vessels, movement of the chest wall during respiration and cardiac motion are the most common sources of this artefact. Involuntary movement such as cardiac motion also causes phase mismapping. Tips to reduce voluntary motion are discussed under *Patient care and safety*.

Phase mismapping is reduced by one or more of the following:

- swapping the phase axis so that the artefact does not interfere with the area under examination (only moves the artefact);
- placement of spatial presaturation pulses between the origin of the artefact and the FOV;
- using respiratory compensation (RC) (see *Gating and respiratory compensation techniques*);
- using echocardiogram (ECG) gating or peripheral (Pe) gating (see *Gating and respiratory compensation techniques*).
- selecting GMN.

Aliasing

Aliasing occurs when anatomy that lies within the boundaries of the receiver coil (and therefore produces signal) exists outside the FOV. If the data from the signal received are under-sampled by the system, there is a duplication of frequency and phase values so that anatomy that exists

outside the FOV is allocated a pixel position within the FOV. This anatomy is therefore 'wrapped' into the image.

Aliasing can occur along both the frequency encoding axis (frequency wrap) and the phase encoding axis (phase wrap). Frequency wrap is largely eliminated with the use of digital filters that filter out signal originating outside the FOV. Phase wrap is reduced by:

- increasing the FOV to the boundaries of the coil;
- over-sampling in the phase direction;
- placing spatial presaturation pulses over signal-producing anatomy.

4

Chemical shift

Chemical shift artefact is caused by the dissimilar chemical environments of fat and water. This results in a precessional frequency difference between the magnetic moments of fat and water and is called chemical shift. Its magnitude significantly increases at higher field strengths. Chemical shift artefact causes a displacement of signal between fat and water along the frequency axis. It is reduced by:

- scanning with a low field-strength magnet;
- removing either the fat or water signal by the use of STIR/chemical/ spectral presaturation, the Dixon technique (see *Chemical misregistration* below);
- broadening the receive bandwidth;
- reducing the size of the FOV.

Chemical misregistration

Chemical misregistration is also caused by the difference in precessional frequency between fat and water. However, this occurs because as fat and water are precessing at different frequencies, they are in phase with each other at certain times and out of phase at others. When the signals from both fat and water are out of phase, they cancel each other out so that signal loss results. This artefact mainly occurs along the phase axis and causes a dark ring around structures that contain both fat and water. It is most prevalent in GRE sequences and it can be used positively to reduce the signal from fat (Dixon technique). To reduce chemical misregistration:

- Use SE or FSE pulse sequences.
- Use a TE that matches the periodicity of fat and water so that the echo is generated when fat and water are in phase. The periodicity depends on the field strength (approximately 4.2 ms at 1.5 T and 7 ms at 0.5 T). The Dixon technique involves selecting a TE at half the periodicity so that fat and water are out of phase. In this way the signal from fat is reduced. This technique is mainly effective in areas where water and fat co-exist in a voxel.

4

Truncation

This is caused by under-sampling of data at the interface of high and low signal. It occurs along the phase axis and produces a dark band running through a high signal area. It is most commonly seen in the cervical cord, where it is specifically known as Gibbs artefact. Truncation is mainly reduced by increasing the number of phase encoding steps.

Magnetic susceptibility

Magnetic susceptibility artefact occurs because all tissues magnetize to a different degree depending on their magnetic characteristics. This produces a difference in their individual precessional frequencies and phase. The phase discrepancy causes dephasing at the boundaries of structures with a very different magnetic susceptibility, and signal loss results. It is commonly seen on GRE sequences when the patient has a metal prosthesis in situ but is also visualized at the interface of the petrous bone and the brain on coronal incoherent (spoiled) GRE images. Magnetic susceptibility can be used advantageously when investigating haemorrhage or blood products, as the presence of this artefact suggests that bleeding has recently occurred. Magnetic susceptibility is reduced by:

- using SE or FSE pulse sequences;
- removing all metal items from the patient before the examination.

Conclusion

The main artefacts encountered in MRI are described here. In addition, phase artefact caused by pulsation of great vessels, CSF flow and cardiac and respiratory motion are compensated for by using appropriate software and these are discussed in the next section. Table 4.1 summarizes artefacts and how they may be remedied.

5

Gating and respiratory compensation techniques

Introduction

This section refers to the mechanisms and correct placement of gating leads and respiratory bellows. The basic concepts of these techniques are summarized below. Only a brief overview is provided here. For a more detailed explanation please refer to Chapter 8 of *MRI in Practice* or an equivalent text.

Cardiac gating (ECG gating)

Cardiac gating uses the electrical signal detected by leads placed on to the patient's chest to trigger each RF excitation pulse. In this way, each image is always acquired at the same phase of the cardiac cycle, so that phase mismapping from cardiac motion is reduced. There are several factors to take into account when using cardiac gating.

Lead placement

There are usually four leads that are colour coded for easy use. Some systems may only use three leads. In addition, not all systems use the same colour coding but the principle of their placement is the same. Leads can be placed either anteriorly on the chest, or posteriorly on the patient's back. Anterior placement is usually simpler as the landmarks are easier to find. In addition if the leads are placed posteriorly, the patient lies on them during the examination, which may be uncomfortable. The anterior lead placement is described here but if the trace on the ECG monitor is poor, the leads can be placed posteriorly in a mirror image to the anterior leads.

This may improve the trace. Lay the patient supine on the examination couch. The patient wears a front opening gown for easy access. The lead stickers are then firmly attached to the patient's skin. The leads are usually colour coded thus:

- black
- white
- red (live)
- green (ground or earth).

The white and the red leads are placed across the heart, as the voltage difference between the two produces the ECG trace. The green lead is positioned as close as possible to, but not touching, the red lead as this acts as a ground. The black lead also acts as ground. Some systems may not have colour coding, but directions on lead placement are usually given by the manufacturer. Leads can be placed in a variety of ways as long as the above criteria are met. Described below is the simplest method of lead attachment (Figure 5.1):

- **Black lead** right upper chest below the clavicle
- **White lead** in the midline on the superior aspect of the sternum
- **Red lead** one intercostal space directly inferior to the left nipple
- **Green lead** lateral to the red lead but not touching it.

The black lead may be omitted if it is not available on the system. Once the leads are attached and plugged into the system, check that the ECG trace is satisfactory. Traces vary according to rate, rhythm and cardiac output. These in turn depend on the activity of the heart, which is often altered by certain disease processes. Arrhythmias and poor cardiac output (which may be why the patient is being examined) are common problems. The signs of a good trace are:
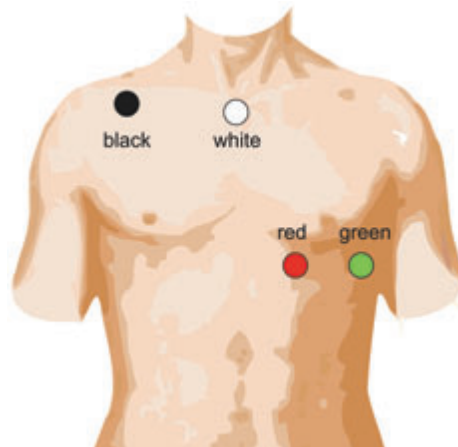
Figure 5.1 The correct placement of gating leads.

Figure 5.2 A normal ECG trace and the correct placement of the triggering threshold relative to the R wave.
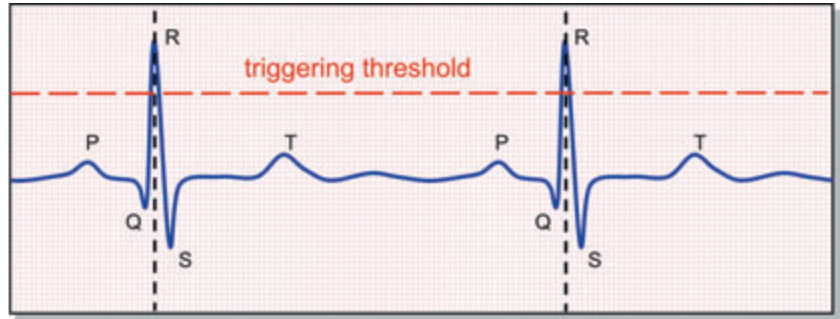
- a regular rate – the PQRST complexes are spaced evenly apart;
- the R wave is significantly larger than the T wave;
- the PQRST complex has good amplitude (Figure 5.2).

If the trace is satisfactory, the patient is placed within the magnet bore. This action frequently alters the trace, and often does so to such an extent that the trace is no longer acceptable. The commonest problem is an elevation of the T wave so that the system cannot distinguish it from the R wave. If this occurs, or if the original trace is unsatisfactory, several measures can be taken.

How to improve the trace

- Always ensure that the electrodes are firmly attached to the chest wall. In male patients, shave any chest hair in the region of the electrodes and clean the skin with alcohol. This removes grease that may prevent proper attachment. After the skin is dry, the electrodes are attached.
- Make sure that the leads are firmly attached to the stickers in the correct order.
- The leads may be swapped around or placed posteriorly to improve the trace. Initially, swap the black and the white leads or the red and the green leads. If this fails to improve the trace, try any other variation of lead placement.
- Place the patient inside the magnet feet first. Patients are usually positioned head first into the magnet for examinations of the chest; however placing them feet first is often beneficial, especially if the problem is an elevated T wave.
- Movement of the cable leads causes irregularities of the trace. Ensure that they are immobilized (see *Cable safety* below), and that the patient does not touch them during the examination. In addition coughing or sneezing can interrupt the trace, so ask the patient to try not to move during the acquisition of data.

5

- Change to peripheral gating or pseudogating (dispensing with gating and setting a TR that is equal to the RR interval).

If after all these measures are taken the trace is still poor, the problem could be a faulty monitor or software problem. Gating is often unreliable and there are occasions when the operator has to make do with the trace displayed. In our experience awful traces can lead to excellent images, and vice versa.

Cable safety

The cables that connect the leads to the system are conductors and are therefore capable of carrying considerable current. During the examination, the majority of the cables lie within the RF field and therefore high currents are induced within them. This current potentially results in the cables storing and transmitting heat to the patient. Although every cable is heavily insulated, a build-up of heat is possible, and this can cause minor burns if the cables are in direct contact with the skin. In addition if the insulation is damaged, high currents could be transmitted to the patient. To avoid this:

- Check the cable insulation for damage at regular intervals, not just when gating is required. If they are frayed or split do not, under any circumstances, use them.
- When positioning the cables, avoid looping and cross-over as their point of contact induces additional heat.
- Ensure that the cables do not touch the bore when the patient is inside the magnet. Run the cables down the middle of the patient. Looping them over the patient's foot prevents them from slipping to the side during the examination.
- Place foam pads between the cables and the patient's chest, and ensure that there is a layer of gown or blanket between the cables and the patient's skin.
- Tape the cables and pads to the side of the table. This ensures that they cannot slip out of place during the examination. In addition, this prevents movement of the cables that can interfere with the trace.

Peripheral gating (Pe gating)

Peripheral gating uses a photo sensor attached to either a finger or toe to detect the increase in volume in the capillary bed during systole. This affects the amount of light returned to the sensor and a waveform is produced. The waveform does not have the characteristics of the ECG trace, but the peaks of the waves approximately correspond to the R wave (about 250 ms after the R wave). This waveform is displayed on the monitor. A good trace has:

- equally spaced peaks
- significant amplitude.

If the trace is unsatisfactory:

- Ensure that the photo sensor is firmly attached with the light source adjacent to the skin.
- Ensure the finger or toe is warm and well perfused. Placing it in warm water or rubbing it is often beneficial.
- Swap the sensor to the left hand as the left arm receives arterial blood directly from the aorta (rather than through the innominate artery) and sometimes has a larger pulse.

Gating parameters

For **T1 weighting** and ECG/Pe gating   use 1 R to R interval.

For **PD/T2 weighting** and ECG/Pe gating   use 2 or 3 R to R intervals.

Note: Other parameters used for gating depend on the system. However, the following usually suffice:

Trigger window   15% of the R to R interval.

Delay after trigger   minimum permissible to allow maximum slice number.

Slices are usually acquired evenly across the available imaging time, although cardiac motion is sometimes reduced if slice acquisition is delayed until diastole.

Cine imaging

Cine, balanced GRE and coherent GRE are beneficial to visualize heart function, blood flow and heart wall motion. For example, the restriction of flow through a coarctation or poorly functioning valve in the heart can be clearly visualized using cine. Good contrast between flowing blood and surrounding lung or cardiac tissue is important. Therefore the implementation of a steady state sequence that enhances the signal intensity of blood is necessary. In addition, the application of GMN in coherent GRE and the balanced gradients in balanced GRE not only reduces flow artefact, but also increases the signal from flowing blood thereby improving CNR.

The efficiency of cine is mainly governed by the correct selection of the number of cardiac phases acquired for each slice during the TR. Data acquisition (data points) should coincide as closely as possible to these phases. If the system cannot match each phase with a data point, cine imaging is less efficient.

Unfortunately, cine images are often plagued with artefact. If compatible, RC effectively reduces respiratory ghosting. Alternatively, breath-holding single slice coherent GRE images eliminate respiratory motion. Susceptibility and misregistration artefacts are common due to gradient rephasing in GRE sequences. Reducing the TE decreases susceptibility problems, and selecting a TE when fat and water are in phase minimizes misregistration.

Respiratory compensation (RC)

There are many forms of respiratory compensation including:

- breath-holding (patient holds their breath during the acquisition);
- navigators (a ROI is placed over the diaphragm and the system throws out data that coincide to maximum chest wall motion);
- respiratory triggering (acquisition of data is limited to minimum chest wall motion);
- respiratory compensation (RC) (phase encodings and therefore K space lines filled are re-ordered during the acquisition to minimize artefact).

The latter two techniques are achieved by placing expandable air-filled bellows around the patient's chest. The movement of air back and forth along the bellows during inspiration and expiration is converted to a waveform by a transducer. In RC the system then orders the phase encoding gradients so that the steep slopes occur when maximum movement of the chest wall occurs, and reserves the shallow gradient slopes for minimum chest wall motion. In this way most of the signal is acquired when the chest wall is relatively still and therefore phase ghosting is reduced. Respiratory triggering is sometimes not as efficient as RC at reducing artefact but does have the advantage of being compatible with phase reordering sequences such as FSE. The success of respiratory bellows depends on the following:

- Ensure that there is no vacuum within the bellows as this inhibits the back and forth movement of air during respiration. This may entail disconnecting the bellows in between examinations and ensuring that they are kept on the ground until they are reattached. This guarantees that no air pockets collect in the bellows or connecting tubing. Some systems, however, require that you do not disconnect the bellows. Please refer to the manufacturer's specifications.
- Place the bellows so that the corrugating portion lies over the anterior chest wall.
- Place the bellows diagonally across the chest and upper abdomen. This ensures that the bellows 'catch' both thoracic and abdominal movements during respiration (Figure 5.3).
- Attach the bellows firmly. The bellows must be tight enough so that movement of the corrugated portion can be seen clearly during

respiratory
compensation
bellows
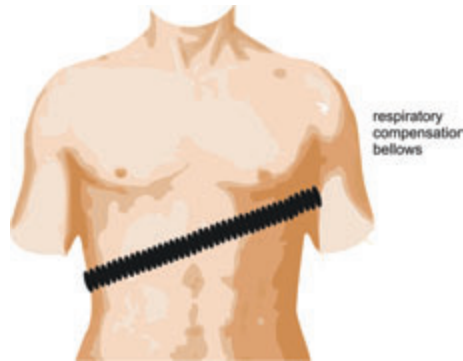
Figure 5.3 Correct positioning of the respiratory bellows to 'catch' both thoracic and abdominal respiration.

quiet respiration. However, if the bellows are too tight, the patient may become uncomfortable.

- Ensure that the bellows are firmly plugged into the transducer.
- If the images show large amounts of respiratory mismapping, or the system informs you that compensation is not working adequately:

  - Check that the bellows have not become loose or unattached.
  - Ask the patient to breathe quietly. Uneven breaths can confuse the system.

- If the patient is small or a child, the bellows may not fit snugly and therefore their action can be compromised. Foam pads placed between the bellows and the patient are usually beneficial.

Conclusion

Gating and respiratory compensation are commonly utilized to examine the chest and abdomen, although gating also has uses in imaging the brain, spinal cord and in cine. The correct use of these techniques can have a profound influence on image quality. If you are unfamiliar with the use of gating, it is often worth practising its implementation on volunteers so that all staff are prepared for its use on sick patients.

6

Patient care and safety

Introduction

This section refers to the *Patient considerations* heading considered for each examination in Part 2. Only a brief overview is provided here. For a more detailed explanation please refer to Chapter 10 of *MRI in Practice* or an equivalent text.

Any patient motion, whether it is due to fear or discomfort, is likely to degrade the image whatever its SNR and resolution characteristics. When a patient steps into an MRI facility he or she becomes the responsibility of the unit personnel. This responsibility extends from the patient's magnetic safety and medical condition, to providing a relaxing environment and a smoothly running facility. It is essential for legal and ethical reasons to ensure that all staff, including radiologists, radiographers, technologists, nurses, and clerical and ancillary personnel, are competent and are aware of their role in providing optimum patient care.

Patient safety

The main aspect of patient safety in any MRI facility is magnetic safety. It is essential that all patients, relatives, and other medical or non-medical personnel are prevented from entering the magnetic field until they have been properly screened. Physical barriers, such as doors and large warning signs, are common ways of achieving this. Clerical personnel (who are usually situated at the entrance to the unit) should be aware of who is present in the facility and whether they have been checked for magnetic safety. Thorough screening of each patient and anyone who is to enter the field is extremely important. Failure to do so may result in injury or even death. All centres should have a proper screening policy which includes checking for:

- pacemakers
- aneurysm clips
- intra-ocular foreign bodies
- metal devices or prostheses
- cochlear implants
- spinal implants

- possibility of early pregnancy
- removal of all jewellery, credit cards, money, watches, etc.

Most facilities provide a screening form that patients, relatives and other persons fill in before entering the magnetic field. This ensures that all important questions have been addressed, and provides a record that screening has taken place. This may be very important if an accident subsequently occurs. Any additional items, such as unremovable jewellery and splints, are thoroughly checked for safety before the patient and their relatives enter the magnetic field. It may be necessary to insulate the item by placing bandages between it and the patient's skin. If the patient or relative has any unusual prosthesis or implant such as a heart valve, its magnetic safety must be established **before** they are taken into the magnetic field.

The safety of intra-cranial aneurysm clips has been the subject of debate for some years. Ferromagnetic clips must not be scanned. Until recently it was considered safe to scan non-ferromagnetic clips. However, studies have shown that some non-ferromagnetic clips can be deviated by a magnetic field. The latest directive is that all clips should be tested for magnetic safety prior to insertion. If this has not been possible, non-ferromagnetic aneurysm clips are still contraindicated for MRI.

Pacemakers are still considered a contraindication to MRI in most centres as the magnetic field alters the reed switch function of the pacemaker. This can lead to arrhythmias and, in certain patients, cardiac arrest. However some cardiac centres have scanned patients with pacemakers if a decision has been made that the benefits of the scan outweigh the risks and if expert help is immediately on hand should the pacemaker cease to function correctly. MR safe pacemakers have been developed but are not currently widely available. Therefore you must always assume a pacemaker is unsafe.

It is usually advisable to ask the patient to change into a gown, as this avoids the problem of ferromagnetic items inadvertently entering the magnetic field inside pockets. Either clerical, nursing or radiographic staff usually perform the magnetic screening procedure. However, it is important to remember that whoever screens the patient, ultimate responsibility falls on the person who takes the patient into the field. It is also necessary to appreciate that in some unshielded units, the magnetic field may extend beyond the confines of the examination room.

There are many other aspects to patient safety within the unit. Care must be taken when transferring patients either on to trolleys or into the examination room. This is especially important if the patient is physically disabled, traumatized or in pain. Non-slip flooring, and trolleys with an adjustable height and lockable brakes, not only ensure that patients are transported in safety, but also prevent injury to unit personnel. In addition, any equipment that comes into contact with the patient during the examination must be carefully checked on a regular basis. This includes gating cables (see *Gating and respiratory compensation techniques*), mon-

itoring equipment (see *Paediatric imaging* in Part 2), and other devices such as coil holders.

The safety of coils and cables is also important (*Coils* under the heading *Equipment* in the section *How to use this book),* as it is not unusual for them to heat up during the examination. Ensure that there is adequate insulation between the coils and their cables and the patient's skin. Small foam pads, sheets of paper or the patient's gown usually suffice. In addition, if patients have a metal prosthesis in situ, they may experience some warmth or discomfort during the examination. It is important to warn the patient that this might occur and to provide them with an alarm bell to ring during the study, should any problems arise. Loud gradient noise also has safety implications, especially if the patient has very sensitive hearing. It is therefore essential to provide the patient with earplugs to prevent hearing impairment. This is especially necessary when ultrafast imaging is employed, as the gradient noise associated with these sequences often exceeds recommended levels.

Lastly, when EPI sequences are used, some patients have reported experiencing mild cutaneous sensations, muscle twitching and flashing lights in their eyes. This is due to the rapidly changing magnetic field. To reduce the probability of peripheral nerve stimulation in EPI sequences, the frequency encoding direction should be R to L for all axial EPI sequences in the brain. Additionally, patients should be instructed to place their arms by their sides and to not cross their ankles to prevent a loop that can precipitate excessive induction of current. It is advisable to warn the patient that these sensations may occur if rapid sequences are utilized. It is also necessary to provide the patient with an alarm bell during the examination should any ill-effects occur.

Patient counselling

The emotional well-being of a patient is just as important as their physical condition. Many patients are not only anxious about the examination, but are also aware that the outcome of the study may affect their subsequent treatment and/or prognosis. Ensuring that the patient is calm and relaxed during the procedure is the responsibility of all unit personnel. The clerical staff are usually the first people to come into contact with the patient, and it is therefore important that they are welcoming and understanding of the patient's emotional needs. A pleasant reception environment further enhances a patient's well-being. In addition, a smooth-running department, where patients are scanned at their designated appointment time, nearly always reassures the patient. If the schedule is running late, or an emergency is fitted in, ensure that the patients are aware of the circumstances and given an approximate time for their examination.

Properly informed patients are usually more comfortable with the examination than those who are fearful of the unknown. An information leaflet sent with the appointment time is a very effective way of preparing

a patient for their visit to the unit. Once they have arrived, a careful explanation of the procedure including positioning, gradient noise, contrast injections, and the approximate length of the examination is necessary. If equipment such as gating leads or respiratory bellows is required, the explanation is expanded to include the reasons for the use of such accessories, and how they may affect the patient. Any special requirements of the patient, such as breath-holding, opening the mouth, or fixing the eyes, must be thoroughly explained before the examination. If the patient does not understand these requirements, the whole examination may be void. It is probably preferable for the radiographer/technologist to provide this explanation, as it not only establishes a relationship with the patient, but also alerts the radiographer to specific anxieties.

When the patient is transferred into the examination room, the sight of the magnet bore and unfamiliar surroundings commonly increase their anxiety. The technologist should be prepared to repeat the explanation of the procedure if necessary, and address any concerns that the patient might have.

Claustrophobia is a common problem in MRI examinations. The enclosing nature of the bore, and equipment such as the head coil, invariably exaggerates any claustrophobic or nervous tendencies. Listed below are a few tips on avoiding claustrophobia:

- If the coil has a mirror, use it and make sure that it is adjusted so that the patient can see out of the magnet.
- If possible examine the patient prone, as this often means that the patient can see out of the magnet. This strategy is mainly beneficial when imaging the pelvis, abdomen, chest, and areas of the upper and lower limbs, such as femora and wrists.
- Remove the pillow under the patient's head as this increases the distance from the patient's face to the roof of the bore of the magnet.
- Tell the patient to close their eyes or place a piece of tissue paper over their face. Some patients dislike this, but others are comforted by the knowledge that if they open their eyes by accident, they will be unable to see the bore of the magnet.
- Use the bore light and fan as they increase the brightness and air circulation.
- Explain that the bore is open at both ends. These few words are often all that is needed to reassure a patient.
- Tell the patient that they can come out of the magnet at any time and that they may refuse the examination without disruption to the facility. This makes the patient feel that they are in control.
- Encourage a friend or relative to accompany the patient during the examination.
- Keep the patient informed over the system intercom of the length of the sequences and the progress of the examination.
- Remember to provide the patient with an alarm bell that he or she can press to alert the radiographer/technologist during the study.

- If these measures fail, a successful examination is usually possible after sedation (see *Sedation and anaesthesia* in the section on *Paediatric imaging* in Part 2*)*.

Using the system intercom, the radiographer/technologist updates the patient during the study on the length of each sequence and the necessity of keeping still. It is extremely reassuring for the patient to hear a familiar voice and to be kept informed on how the examination is progressing. This is also an opportunity to check on the well-being of the patient. There are several medical conditions that may affect how the patient is handled in the unit. Examples of these are blindness, deafness, epilepsy, breathlessness and physical or mental disability. The imaging technique may have to be adapted accordingly. These, and other specific conditions, are described in more detail in Part 2. Some coils are fitted with mirrors to enable the patient to see out of the magnet bore, and it is worth remembering that they may also be able to see out of the examination room window and observe the technical staff at work. Therefore all unit personnel should be aware that the patient may be watching their every move and facial expression!

6

Patient immobilization

Careful immobilization of the patient is always necessary to ensure an optimum study. Immobilization is especially important during lengthy examinations and when the area under investigation is very small and optimum spatial resolution is required. The key to good immobilization is correct positioning, and making the patient as comfortable as possible. Most positions assumed by the patient during an MRI study are in natural relaxed poses, i.e. supine with the arms at the side. However, examinations of the upper limb and breast often involve placing the patient prone with their arms above their head. In addition, some medical conditions may preclude the use of standard positioning. Severe pain and breathlessness are common reasons for modifying the patient's position. It is important to remember, however, that even the most comfortable positions usually become uncomfortable if the patient has to maintain them for long periods of time.

Once the patient is placed correctly on to the examination couch and the coils have been positioned, immobilization is then required. All manufacturers provide foam pads of various shapes and sizes that are used to maintain a certain position. Many are moulded for use with a certain coil. Once immobilized, it is important to ensure that the patient is relaxed as, if effort is required to maintain the position, the likelihood of patient motion is increased. Unless the patient is in pain, it is almost impossible to over-immobilize. It is obviously necessary, however, to ensure that the patient is comfortable with the amount of immobilization used. Other accessories such as sticky tape are beneficial for immobilization purposes of both the patient and coils. Compression bands

placed across the abdomen and pelvis are very effective at reducing bowel motion.

Other pads are useful to increase patient comfort, e.g. a small pad elevating the patient's knees during the examination reduces back pain.

Patient after care

Once the examination is over, remove all immobilization devices, coils, straps and foam pads and carefully transfer the patient back into the waiting area. Patients are often very disorientated after an MRI study. Providing patients with a drink before they leave the unit often calms them, and allows the unit staff to assess their medical and emotional condition. If the patient has received sedation or anaesthesia, it is essential that they have fully recovered before they leave the unit (see *Paediatric imaging* in Part 2). Lastly, patients are usually grateful if they are informed when to see their doctor about the results of the examination.

6

Conclusion

Unless the patient is very relaxed, almost any MRI examination is an ordeal. Therefore the importance of patient safety and care cannot be over-emphasized. Ensuring optimum safety and counselling standards is as important as correct parameter selection. It is often difficult for medical staff to appreciate patient anxieties. The magnetic environment is second nature to unit personnel, but it is a totally new experience for most patients. Always put yourself in the patient's shoes and volunteer to be scanned as often as possible, as this gives the best insight into the patient's experience.

7

Contrast agents

Introduction

Contrast enhancement is extremely valuable in many disease processes including tumours, inflammation and infection. Although these pathologies contain a high water content and are often visualized in T2 weighted images, sometimes there is insufficient contrast between the lesion and surrounding tissue. In addition, T1 weighted images demonstrate a higher SNR and are therefore advantageous, but water and pathology are commonly isointense in these sequences. Therefore it is sometimes necessary to selectively enhance pathology by administering contrast agents. This can be done either indirectly via the intravenous (IV), oral or rectal routes or directly into a structure such as a joint. Only a brief overview is provided here. For a more detailed explanation please refer to Chapter 11 of *MRI in Practice* or an equivalent text. There are two types of contrast agents: those that produce positive contrast and those that result in negative contrast.

Positive contrast agents

The most common positive contrast agent used in MRI is gadolinium (Gd). Gadolinium is a paramagnetic substance that has a relatively large magnetic moment. When introduced into the body, its presence causes increased fluctuations in the magnetic fields of water protons so that they tumble near to the Larmor frequency. As a result there is a transfer of energy to the surrounding lattice and both T1 and T2 relaxation times are reduced. Since T2 relaxation is much shorter than T1, a high concentration of agent is required to produce significant shortening of T2. However, much smaller doses are effective at shortening the T1 relaxation time of water protons thereby increasing their signal intensity on T1 weighted images. Gadolinium is therefore known as a T1 enhancement agent.

Gadolinium is a heavy metal and binds to certain elements in the body such as membranes and the osseous matrix. Therefore gadolinium cannot be excreted unless it is attached to a chelate. This chelate surrounds the gadolinium ion and enables its excretion, mainly through the kidneys. The most common chelate in use is diethylene triaminepentaacetic acid

(DTPA), which binds to eight of the nine binding sites in the gadolinium ion and leaves the last free to facilitate the close approach to water molecules. Other examples of chelates used with gadolinium are gado-pentetate dimeglumine, HP-DO3A, DTPA-BMA and DOTA.

Gadolinium may be given intravenously (IV), orally or rectally or injected directly into a joint. The recommended IV dose of Gd-DTPA and Gd-DTPA-BMA is 0.1 mmol/kg and 0.3 mmol/kg for Gd-HP-DO3A. Oral gadolinium provides positive contrast of the gastrointestinal tract to label the bowel thereby increasing the visualization of abdominal organs such as the pancreas. Oral gadolinium has a neutral taste and is easily mixed with water prior to ingestion. Problems may arise from the bowel 'whiting out', although this can be minimized by careful adjustment of the dose and optimum timing of the scan sequence post-ingestion. Gadolinium may also be injected directly into a cavity such as a joint. Magnetic resonance arthrography is an important technique, especially in the hip, shoulder and ankle.

Other positive agents include manganese, an IV agent used in liver imaging and hyperpolarized helium a T1 ventilation agent used for the evaluation of the lungs.

7

Negative contrast agents

Superparamagnetic agents such as iron oxides and manganese are termed T2 enhancement agents. This is because their presence causes a shortening of T2 decay times and reduced signal intensity. They are taken up by the reticulo-endothelial system and transported to the Kupffer cells of the liver parenchyma. Like gadolinium, superparamagnetic agents are dangerous in their pure form. However, unlike gadolinium, chemical barriers are not used. Instead the iron oxide particles are coated with either hydrophilic polymer or arabinagalactin to provide a physical barrier.

These agents dramatically shorten the T2 relaxation times of normal liver so that it appears dark and lesions appear bright on T2 weighted images. They are, therefore, specifically used for liver imaging and are given IV. A recommended dose is 0.56 mg of iron per kg of body weight. This is diluted in 100 ml of 50% dextrose and given over a 30 min period at a rate of 2–4 mm/min through a 5 micron filter.

Other negative contrast agents include oral agents known as Gastro-mark™, blueberry juice and air, which are used for bowel imaging to delineate the large bowel in pelvic examinations.

Blood pool agents

Intravascular (blood pool) agents differ from standard gadolinium agents in several areas. First and foremost is their persistence in the vessels for an extended period of time rather than diffusing out of the blood stream as occurs with standard extra-cellular fluid space agents. When imaging

with standard agents, maximum concentration, and therefore maximum signal, persists only for several seconds resulting in a small window of opportunity for obtaining high-resolution images. With intravascular agents, not only can data be acquired in the 'first-pass', as with standard agents, but high resolution images can be acquired in the 'equilibrium' phase as well, with high signal persisting well over 30 minutes.

The second major difference is in relaxivity. Relaxivity is an expression of the amount of T1 and T2 shortening provided by the contrast agent. Increasing relaxivity can be obtained by several means; however, in the case of intravascular agents it is accomplished by the reversible binding of the agent to human albumin in plasma. This results in slowed molecular tumbling of the hydrogen protons in albumin and a markedly increased relaxivity and therefore increased signal.

Conclusion

The development of contrast agents has rapidly advanced and their use will increase the diagnostic capabilities of MRI in the future. It is therefore important that MR users keep abreast of these developments so that their optimum and safe use is assured.

7

Part 2　Examination areas

8

Head and neck

8

Table 8.1 Summary of parameters. The figures given are general and should be adjusted according to the system used (Table 2.1)

Spin echo (SE)

short TE	min to 30 ms
long TE	70 ms +
short TR	300−600 ms
long TR	2000 ms +

Fast spin echo (FSE)

short TE	min−20 ms
long TE	90 ms +
short TR	400−600 ms
long TR	4000 ms +
short ETL	2−6
long ETL	16 +

Inversion recovery (IR) T1

short TE	min−20 ms
long TR	3000 ms +
medium TI	200−600 ms
short ETL	2−6

STIR

long TE	60 ms +
long TR	3000 ms +
short TI	100−175 ms
long ETL	12−20

FLAIR

long TE	60 ms +
long TR	3000 ms +
long TI	1700−2200 ms
long ETL	12−20

Coherent GRE

long TE	15 ms +
short TR	≤ 50 ms
flip angle	20°−40°

Incoherent GRE

short TE	min−5 ms
short TR	≤ 50 ms
flip angle	20°−40°

Balanced GRE

TE	minimum
TR	minimum
flip angle	≥ 40°

SSFP

TE	minimum
TR	40−50 ms
flip angle	20°−40°

Slice thickness

2D	thin	2−4 mm
	medium	5−6 mm
	thick	8 mm
3D	thin	≤ 1 mm
	thick	≥ 3 mm

Slice numbers

Volumes	small	≤ 32
	medium	64
	large	≥ 128

Matrix (frequency × phase)

coarse	256 × 128 or 256 × 192
medium	256 × 256 or 512 × 256
fine	512 × 512
very fine	≥ 512 × 512

FOV

small	≤ 18 cm
medium	18−30 cm
large	≥ 30 cm

PC-MRA

2D and 3D	TE	minimum
	TR	25−33 ms
	flip angle	30°
VENC venous	20−40 cm/s	
VENC arterial	60 cm/s	

NEX/NSA

short	≤ 1
medium	2−3
multiple	≥ 4

TOF-MRA

2D	TE	minimum
	TR	28−45 ms
	flip angle	40°−60°
3D	TE	minimum
	TR	25−50 ms
	flip angle	20°−30°

8

Brain

Basic anatomy (Figures 8.1 and 8.2)

Figure 8.1 Sagittal section through the brain showing midline structures.

8
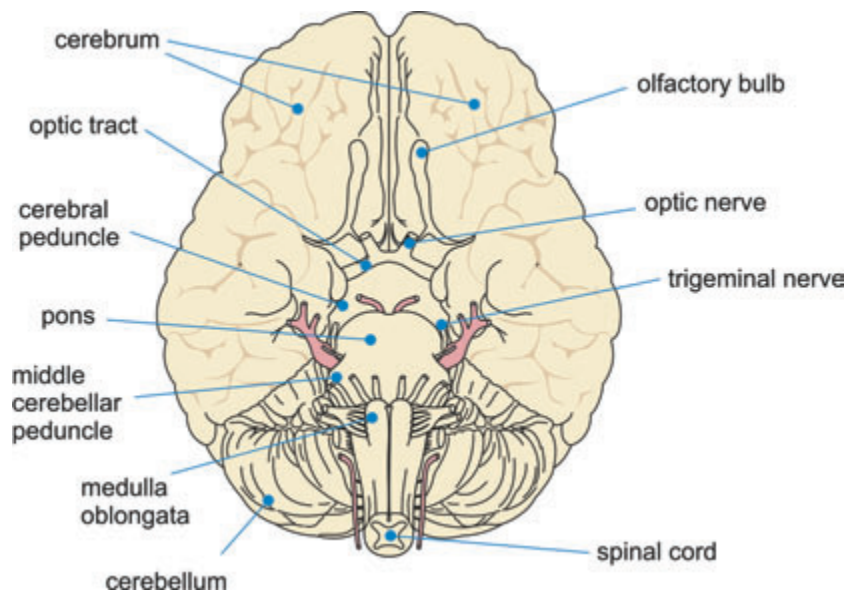
Figure 8.2 Transverse section through the brain showing inferior structures.

Common indications

- Multiple sclerosis (MS).
- Primary tumour assessment and/or metastatic disease.
- AIDS (toxoplasmosis).
- Infarction (cerebral vascular accident (CVA) vs. transient ischaemic attack (TIA)).
- Haemorrhage.
- Hearing loss.
- Visual disturbances.
- Infection.
- Trauma.
- Unexplained neurological symptoms or deficit.
- Pre-operative planning.
- Radiation treatment planning.
- Follow-up (surgical or treatment).

Equipment

- Head coil (quadrature or multi-coil array).
- Immobilization pads and straps.
- Ear plugs.
- High-performance gradients for EPI, diffusion and perfusion imaging.

8

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the interpupillary line is parallel to the couch and the head is straight. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the nasion. Straps and foam pads are used for immobilization.

Suggested protocol

Sagittal SE/FSE/incoherent (spoiled) GRE T1

Medium slices/gap are prescribed on each side of the longitudinal alignment light from one temporal lobe to the other. The area from the foramen magnum to the top of the head is included in the image.

L 37 mm to R 37 mm

Axial/oblique SE/FSE PD/T2 (Figure 8.5)

Medium slices/gap are prescribed from the foramen magnum to the superior surface of the brain. Slices may be angled so that they are parallel to
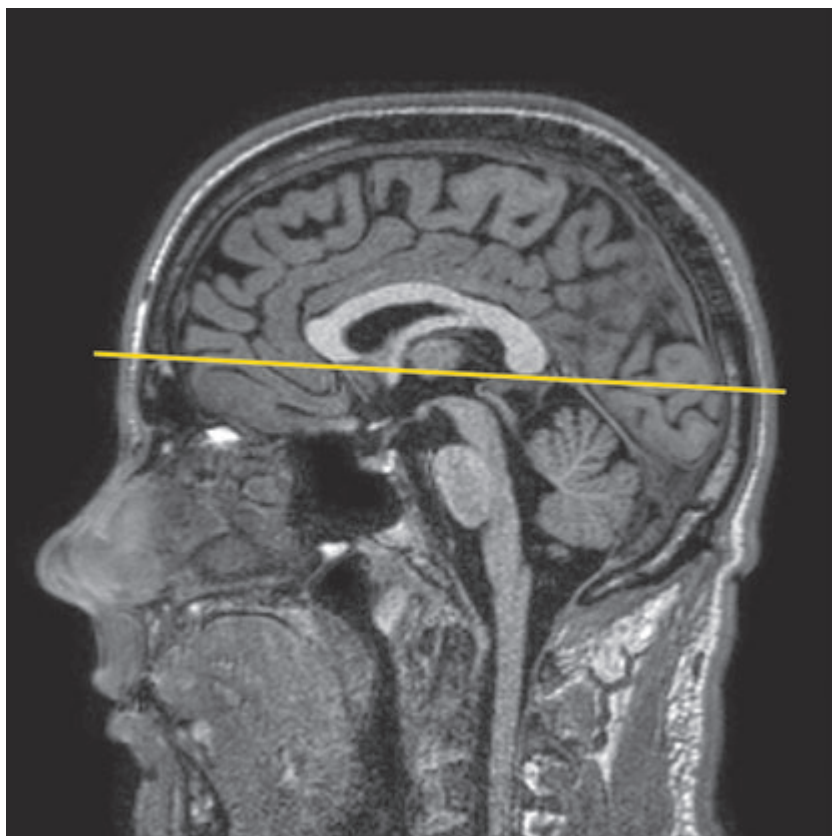
Figure 8.3 Sagittal SE T1 weighted midline slice of the brain showing the axis of the anterior and posterior commissures.

8

the anterior–posterior commissure axis. This enables precise localization of lesions from reference to anatomy atlases (Figures 8.3 and 8.4). Many sites have replaced the PD sequence with FLAIR (see below). SS-FSE or SS-EPI may be a necessary alternative for a rapid examination in uncooperative patients.

Coronal SE/FSE PD/T2

As for Axial PD/T2, except prescribe slices from the cerebellum to the frontal lobe (Figure 8.6).

Additional sequences

Axial/oblique IR T1 (Figure 8.7)

Slice prescription as for Axial/oblique T2.

This sequence is especially useful in imaging the paediatric brain (see *Paediatric imaging* later in Part 2). White matter does not fully myelinate until approximately 5 years of age, therefore in the very young patient, grey and white matter have very similar T1 relaxation times, and the CNR between these tissues is small on SE T1 sequences.

Figure 8.4 Sagittal SE T1 weighted midline slice of the brain showing slice prescription boundaries and orientation for axial/oblique imaging.

8
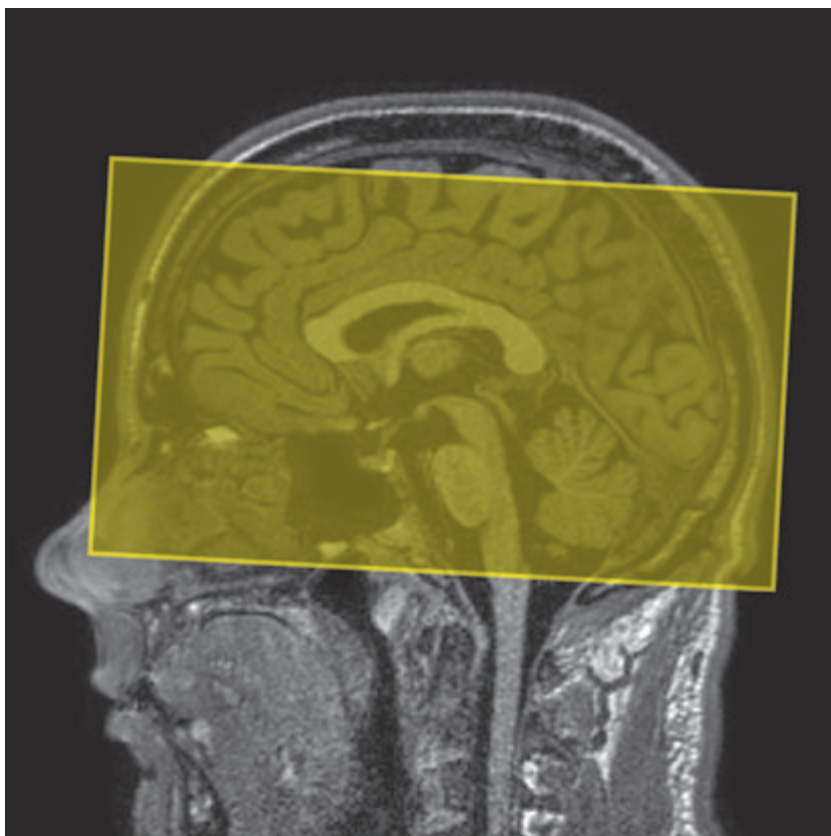
Figure 8. 5 Axial/oblique FSE T2 weighted image of the brain showing normal appearances.
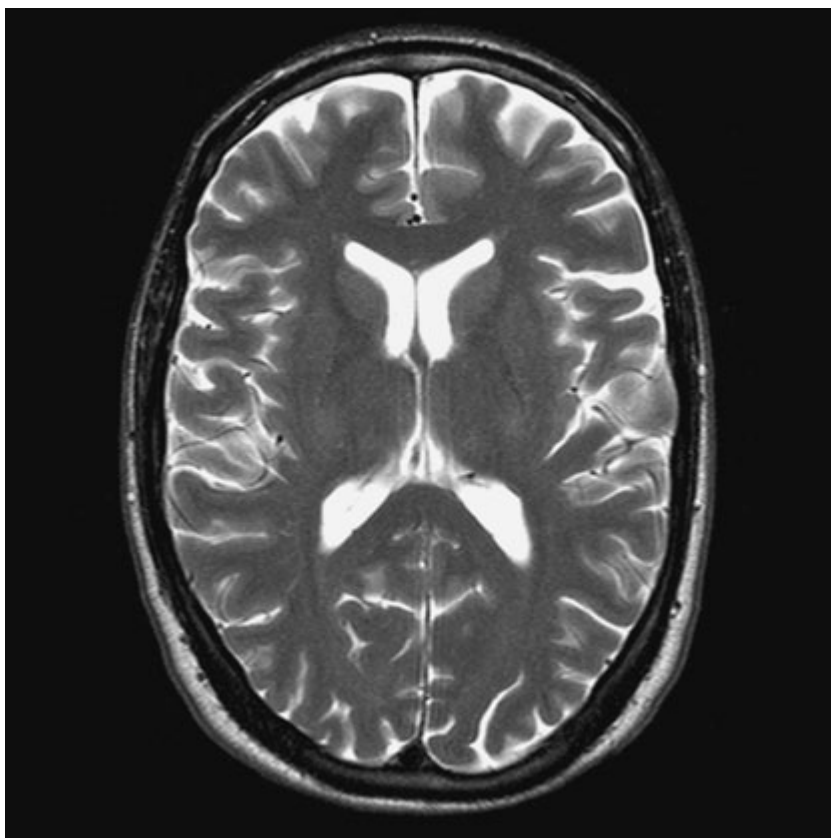
Figure 8.6 Sagittal SE T1 weighted image showing slice prescription boundaries and orientation for coronal imaging.
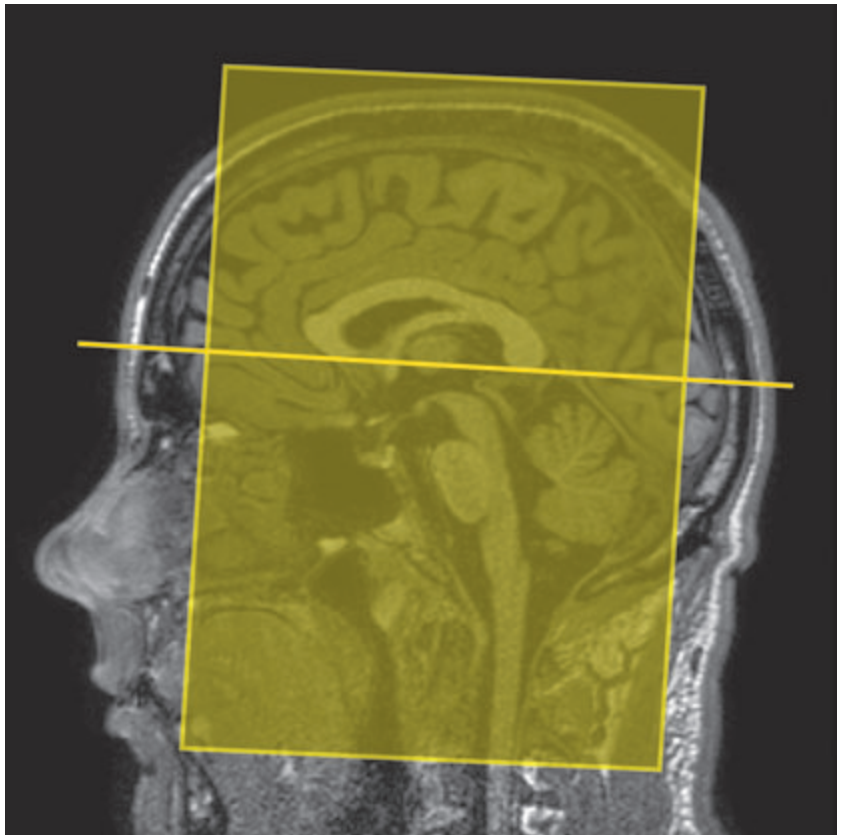
Figure 8.7 Axial IR T1 weighted image using a TI of 700 ms.
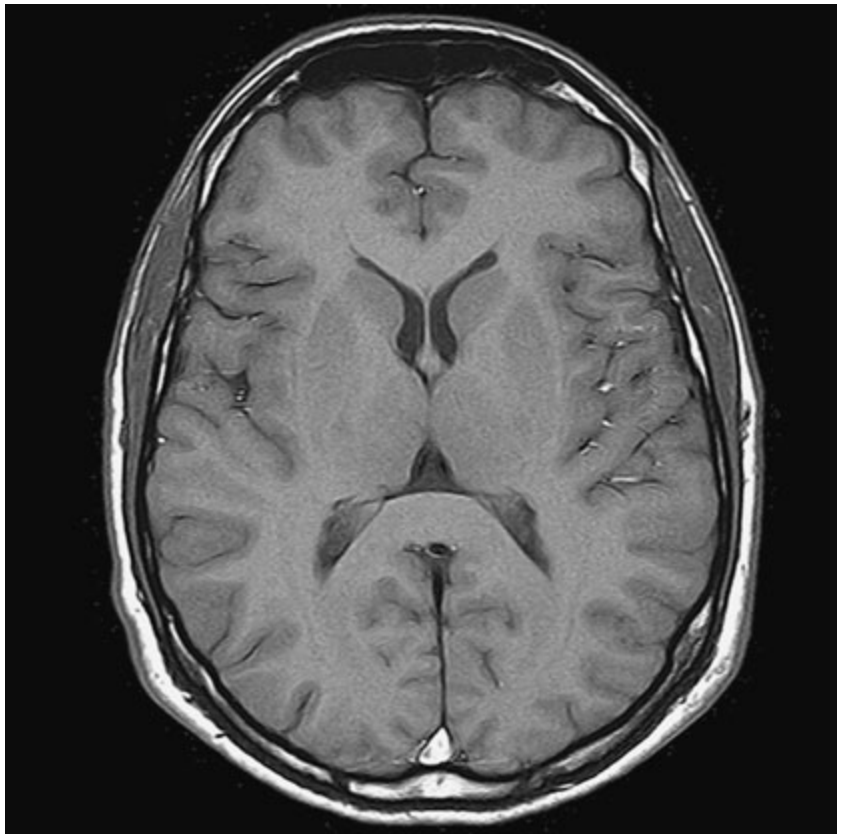
Figure 8.8   Axial/oblique FLAIR image of the brain. Periventricular abnormalities will have a high signal intensity in contrast to the low signal of CSF which has been nulled using a long TI.

8
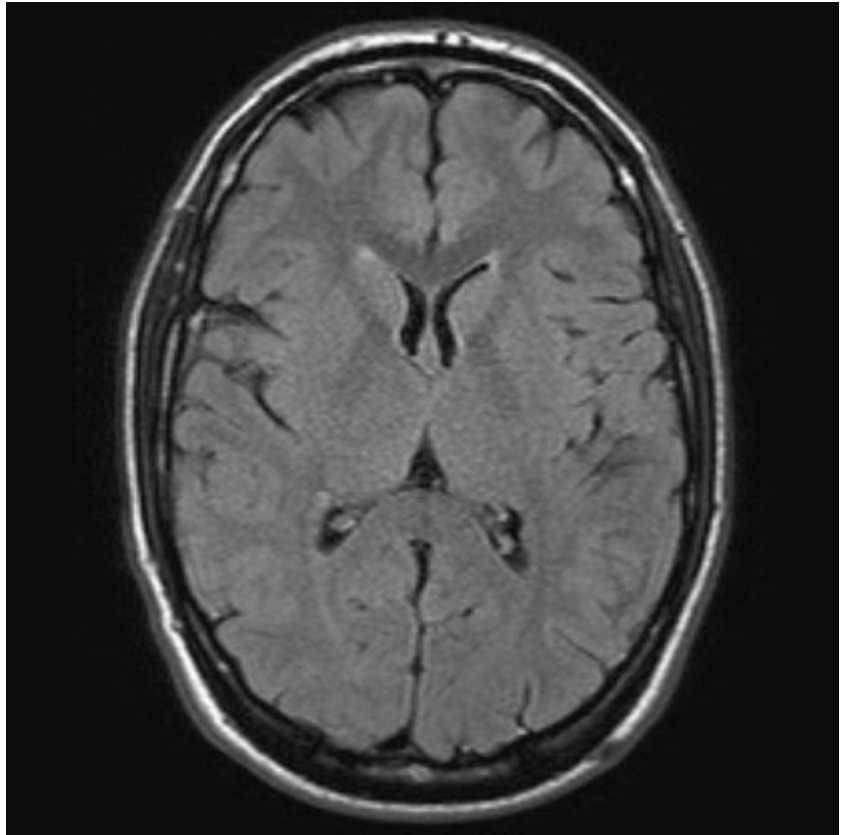
Axial/oblique FLAIR/EPI (Figure 8.8)

Slice prescription as for Axial/oblique T2.

This sequence provides a rapid acquisition with suppression of CSF signal. It may be useful when examining periventricular or cord lesions such as MS plaques.

Axial/oblique SE/FSE/incoherent (spoiled) GRE T1 (Figure 8.9)

Slice prescription as for Axial/oblique T2.

Pre- and post-contrast scans are common especially for tumour assessment.

SS-FSE T2 (Figure 8.10)

Useful for rapid imaging in uncooperative patients.

Figure 8. 9 Axial/oblique incoherent (spoiled) GRE image of the brain.
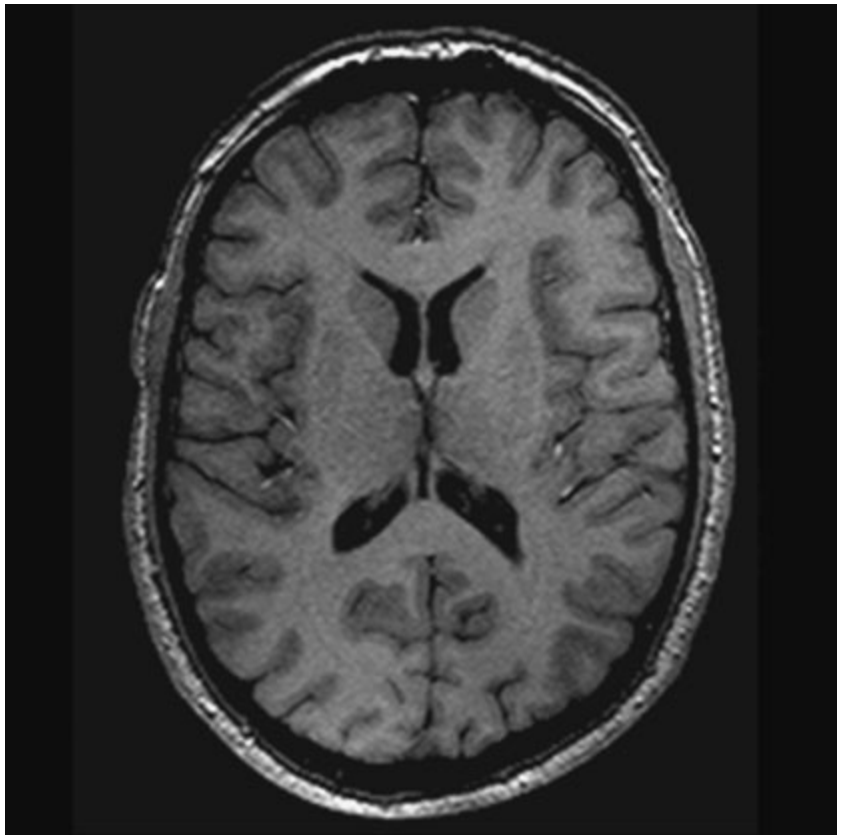
Figure 8.10 SS-FSE T2 weighted image of the brain. The entire brain was scanned in 40 s.
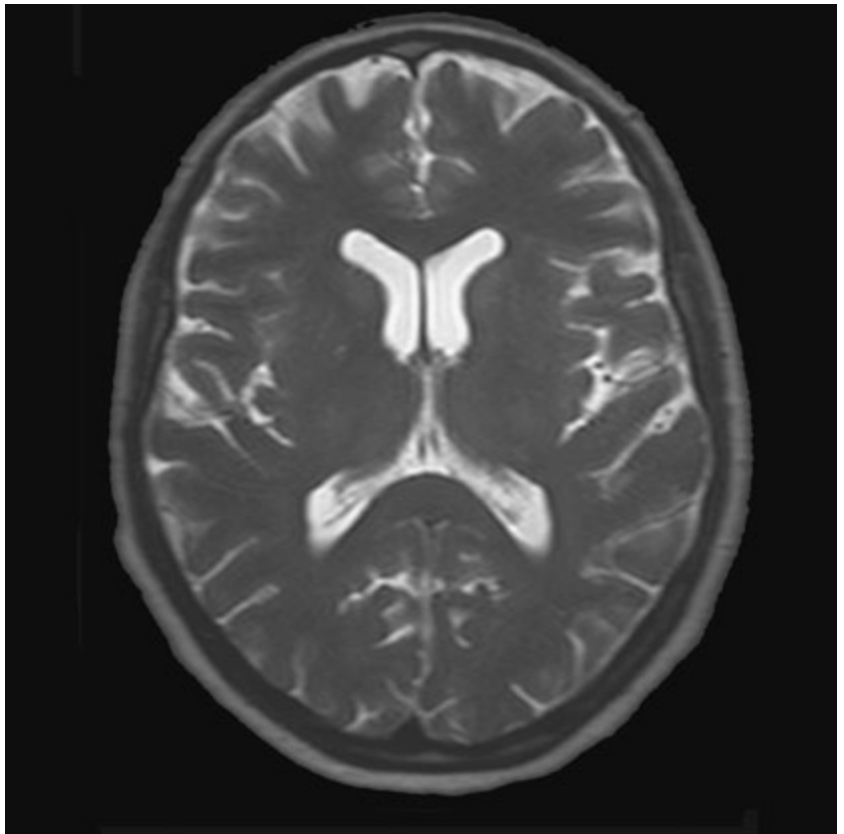
Figure 8.11 Single shot EPI image of the brain. The entire brain was scanned in 14 s.
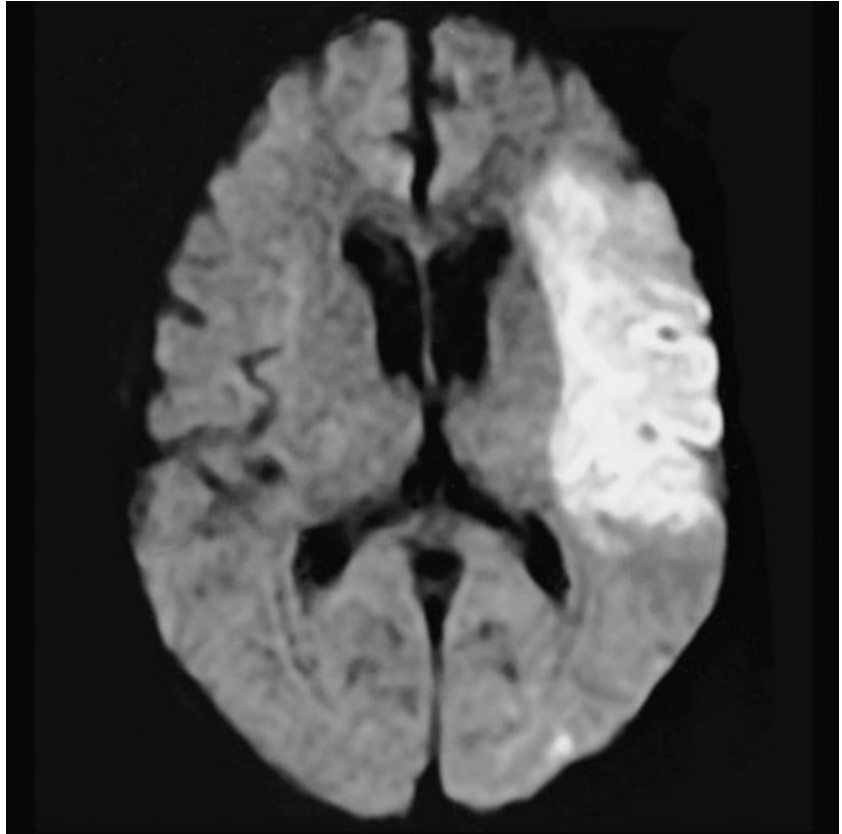
Axial 3D incoherent (spoiled) GRE T1

This sequence is useful for high-resolution imaging of small structures within the brain. If reformatting of slices is desired, an isotropic dataset must be acquired (see *Volume imaging* under *Parameters and trade-offs* in Part 1).

Axial/oblique GRE/EPI T1/T2 (Figure 8.11)

Due to sensitivity to magnetic susceptibilities, these sequences demonstrate haemorrhage better than SE and FSE.

Axial/oblique SE MT

Slice prescription as for Axial/oblique T2.

MT is a useful sequence to improve visualization of lesions such as metastasis, and some low-grade tumours, as grey and white matter loses 30–40% of its signal when a MT pulse sequence is utilized. The CNR between lesions and the surrounding brain is therefore increased (see *Pulse sequences* in Part 1).

Figure 8.12 DWI showing large area of high signal on right. High signal on a DWI can be the result of restricted diffusion or 'T2 shine-through'.
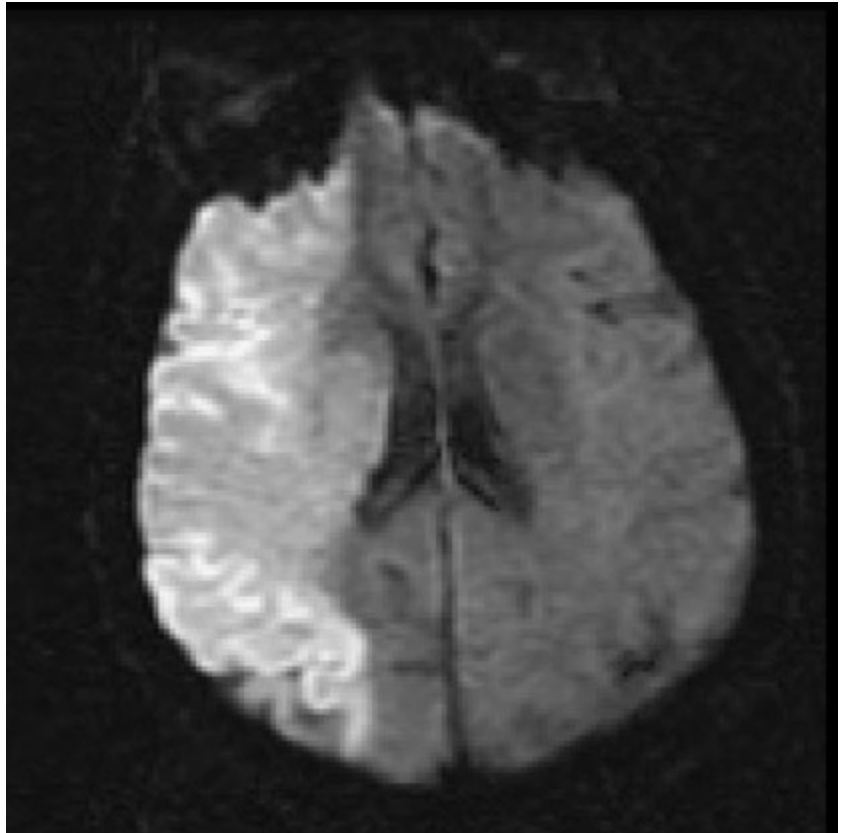
Axial DWI (Figures 8.12 and 8.13)

Slice prescription as for Axial/oblique T2.

This sequence is important in the investigation of early stroke. It is also utilized in paediatric patients to investigate the effects of hypoxia and myelination patterns (see *Paediatric imaging later* in Part 2). A b-value of 800–1000 s/mm^2 is selected (the higher the b-value, the more diffusion weighting). Isotropic diffusion should be acquired (i.e. diffusion gradients applied in all three axes) (see *Pulse sequences* in Part 1).

A DWI sequence is most often acquired using a T2 weighted EPI sequence. In a standard T2 weighted EPI sequence, there is not enough motion (diffusion) of the extra-cellular water during the imaging cycle to result in dephasing of the water protons. Diffusion gradients are therefore utilized to increase the sensitivity to the motion of the extra-cellular water molecules. The b-value controls the amplitude, duration and/or timing of these diffusion gradients and thus determines the amount of diffusion weighting in a diffusion sequence. Increasing the b-value increases the sensitivity to the motion (diffusion) of extra-cellular water in tissue and thus increases the diffusion weighting. The signal in areas of normal

Figure 8.13 Calculated ADC image showing restricted diffusion (acute stroke) as low signal. Small area of high signal in right posterior represents 'T2 shine-through'.

8

diffusion is reduced due to the dephasing of the water protons in the presence of these diffusion gradients. The more restricted the diffusion, the less dephasing of the water protons and higher signal will be seen on the diffusion image. On most MR systems both the b = 0 image (i.e. the T2-weighted EPI image) and the diffusion image with the b value chosen by the operator will be displayed. Some systems may also display three additional images per slice location. These are the images obtained during the diffusion acquisition. The diffusion gradients are applied in each of the three orthogonal planes (X, Y and Z) measuring the diffusion in each of those directions. The data are then averaged to produce the final 'trace' or diffusion-weighted image displayed.

It is important to remember that high signal seen on a diffusion-weighted image may actually be high signal from spins with a long T2-relaxation time 'shining through'. These so-called 'T2 shine-through' effects are eliminated by the calculation and production of an ADC map or image. The apparent diffusion coefficient (ADC) expresses the amount of motion of extra-cellular water. The ADC image is calculated from the b value of 0 and the b value used in the diffusion acquisition (most commonly 1000 mm/s^2 in a DWI exam of the brain) to produce a

'2-point' ADC image (Figure 8.13). In some situations, one may acquire a DWI with two b values. That, along with the b value of 0, would be used to calculate a '3-point' ADC image. In any event, the pixel values in an ADC image represent the ADC of pixels in the image. In areas with restricted diffusion (i.e. low ADC), the pixel values are dark. A high ADC, seen in the presence of mobile water protons will result in a bright pixel on the ADC image. Calculating and producing an ADC image is very important in distinguishing between acute and chronic stokes. Depending on the MR system, the ADC image may be produced automatically or it may require some minor additional processing steps.

Diffusion tensor imaging (DTI)

When the diffusion of water along the three orthogonal directions of the magnet (X, Y and Z) is measured and the average obtained, only isotropic diffusion information is acquired; that is diffusion that is random in direction. In the brain this is seen in grey matter. In white matter, the structure of the tissue 'orders' the diffusion. In white matter diffusion is ordered along the white matter tracts. This type of ordered diffusion is referred to as anisotropy (anisotropic diffusion). In order to image anisotropic diffusion, diffusion in more than three axes is measured. In physics, a tensor is basically motion as a function of direction. DTI is essentially imaging diffusion that is ordered in direction (anisotropic rather than isotropic). At a minimum, DTI must measure the diffusion along at least six axes. In clinical practice twelve or more directions are measured. Due to a loss in SNR as the number of directions measured increases, DTI is particularly useful at high field strengths such as 3 T. DTI is currently used for mapping white matter tracts as fractional anisotropy (FA) maps, or as tractography images (Figures 8.14–8.18).

Axial perfusion imaging

Slice prescription as for Axial/oblique T2.

This sequence provides temporal resolution of enhancing lesions and indicates activity. Injection of a gadolinium bolus should begin immediately after the scan is initiated. Post-enhancement T1 imaging follows the perfusion series (see *Pulse sequences* and its subheading *Dynamic imaging* in Part 1).

The use of an MR compatible contrast injector greatly increases the consistency of perfusion information. Furthermore, in order to optimize the susceptibility effects, a rapid bolus of contrast is necessary. A minimum injection rate of 4 ml/second is preferable. The amount or volume injected may vary depending on concentration of the contrast media, relaxivity of the contrast media, field strength, and/or pulse sequence utilized. At 1.5 T, the strongest effects are seen using a GRE-EPI sequence. If such a sequence is used 0.1 mmol/kg is typically adequate. Due to the increased susceptibility effects seen with a GRE-EPI sequence, only information regarding large vessel perfusion is obtained. If one
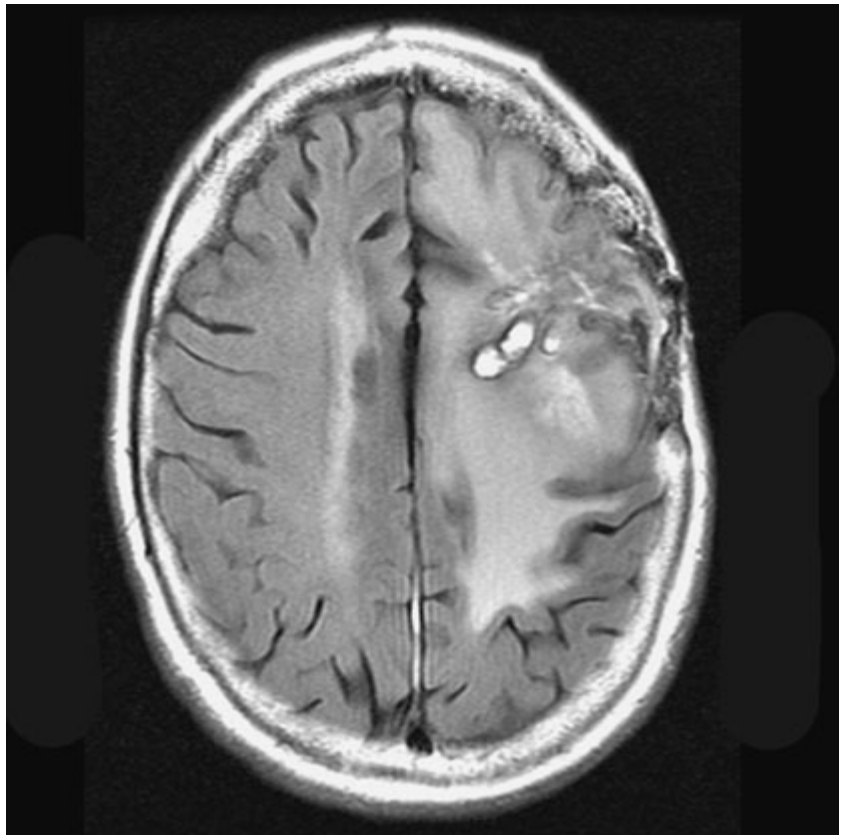
Figure 8.14 T2-weighed FLAIR showing lesion.
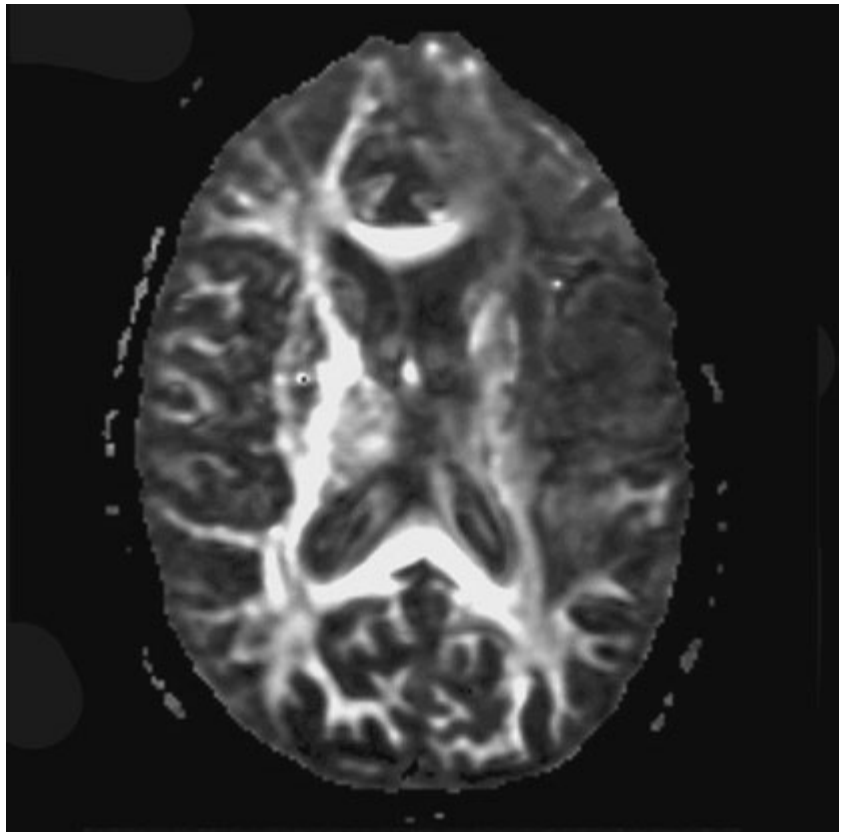
Figure 8.15 Fractional anisotropy (FA) map showing anisotropic (ordered) diffusion in the white matter tracts.
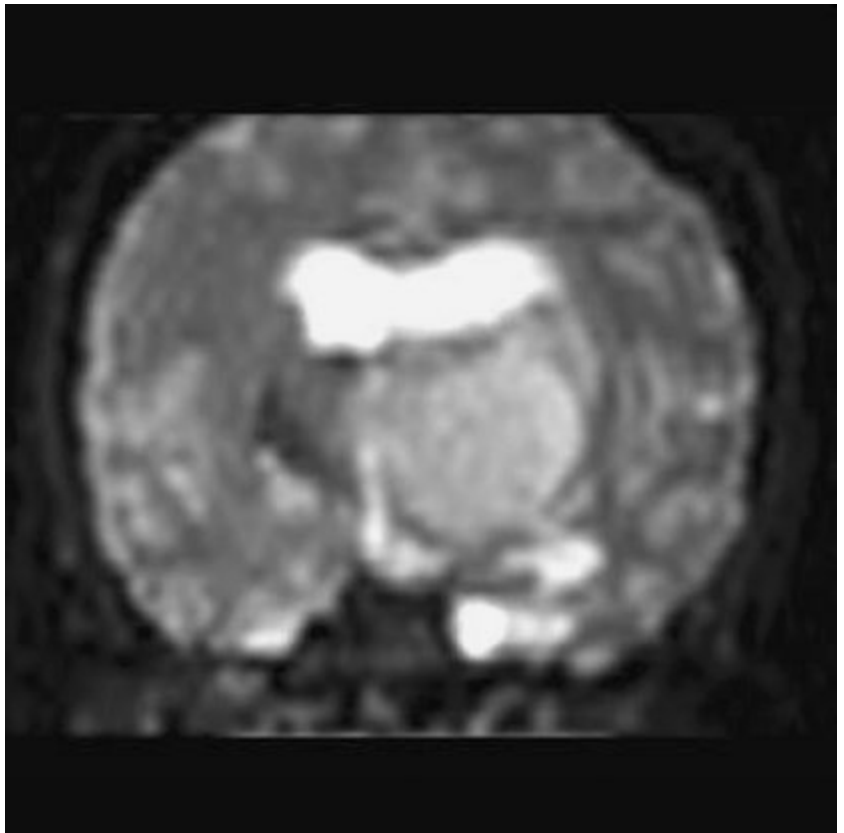
Figure 8.16 Coronal T2-weighted EPI demonstrates lesion.
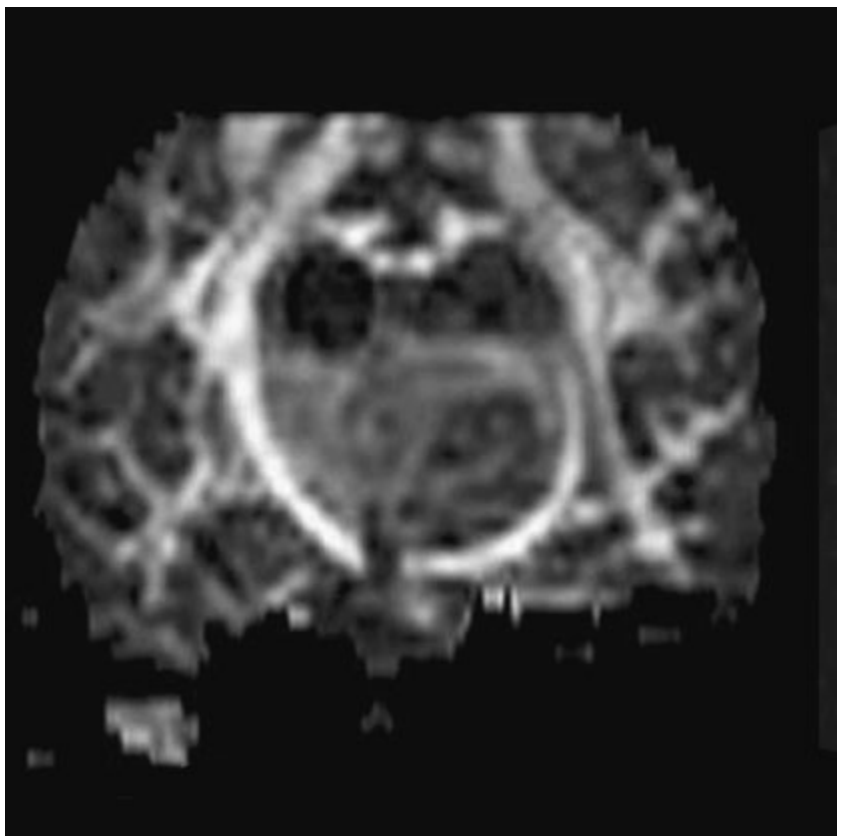
Figure 8.17 FA map shows white matter tracts relative to the lesion.

8

Figure 8.18 Tractography demonstrates tract orientation relative to the lesion.

wishes to obtain information relating to small vessel perfusion, then a SE-EPI sequence should be utilized. It is important to remember however that due to the reduced susceptibility effects obtained with the SE-EPI sequence, a higher dose or concentration of gadolinium may be necessary. Not all gadolinium agents have the same effect on T1 and T2-relaxation times. There are some agents with higher relaxivities (r1 and r2). These agents, when used for perfusion imaging, result in greater signal reduction when compared with the same dose of a standard gadolinium agent due to the increased r2 (relaxivity). At 3.0 T, susceptibility effects are increased as a function of the field strength and allow for either a reduced dose of gadolinium (0.5 mmol/kg) with a GRE-EPI sequence or a standard dose (0.1 mmol/kg) of gadolinium with a SE-EPI sequence. SE-EPI sequences also result in fewer susceptibility artefacts. In summary, the amount of gadolinium used for perfusion imaging is dependent upon the type of contrast agent used, field strength and acquisition technique selected.

When perfusion imaging is utilized for stroke imaging, the area affected by the stroke appears as either an area of late arriving contrast or totally non-perfusing. When imaging a tumour, however, the area of abnormal perfusion will often be demonstrated as an area of hyper-perfusion. The
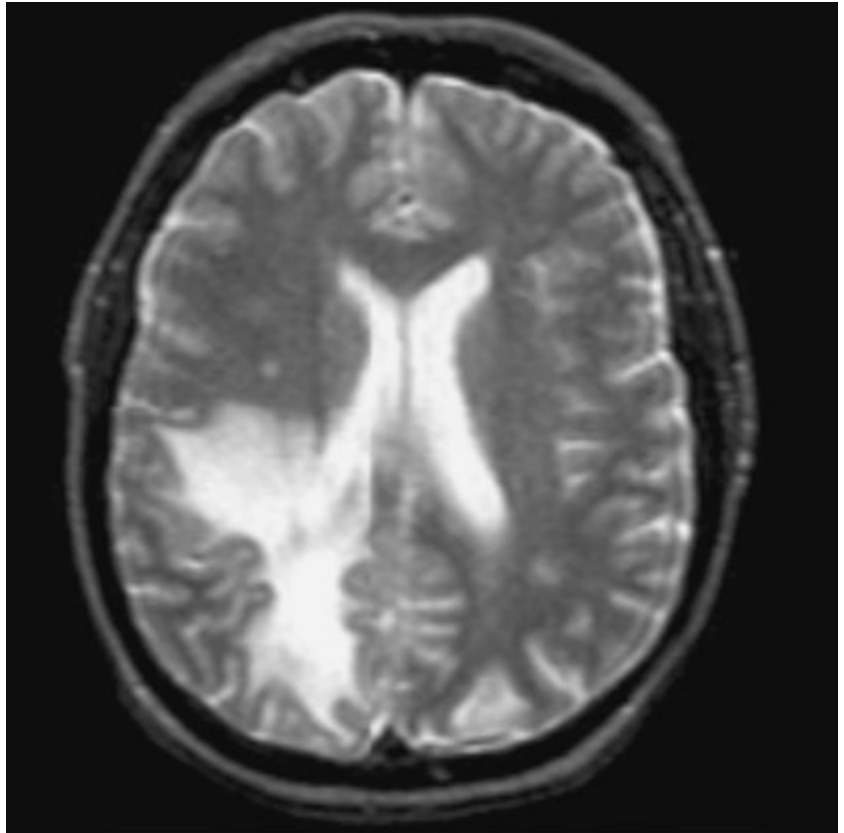
Figure 8.19 T2-weighted image shows large area of oedema following treatment.

8

images in Figures 8.19 and 8.20 illustrate this effect. The area of residual tumour is indistinguishable from the adjacent tissue due to oedema and other changes. The perfusion data clearly show an area of increased or hyper-perfusion indicating residual or recurrent tumour.

Technical Issues

Image optimization

Using a quadrature or multi-coil array will yield high and uniform signal. Using a multi-coil array with greater than four channels however may require the use of a uniformity correction algorithm to produce an image with uniform signal throughout. Regardless of the coil selected, images with excellent SNR and spatial resolution should be easily attainable in reasonable scan times.

FSE is the pulse sequence most often utilized for acquiring PD and T2 weighted images due to its shorter scan times compared with CSE. There is some debate as to whether PD and T2 weighted images should be

Figure 8.20 Perfusion data shows area of hyperperfusion within the oedema indicating recurrent tumour.
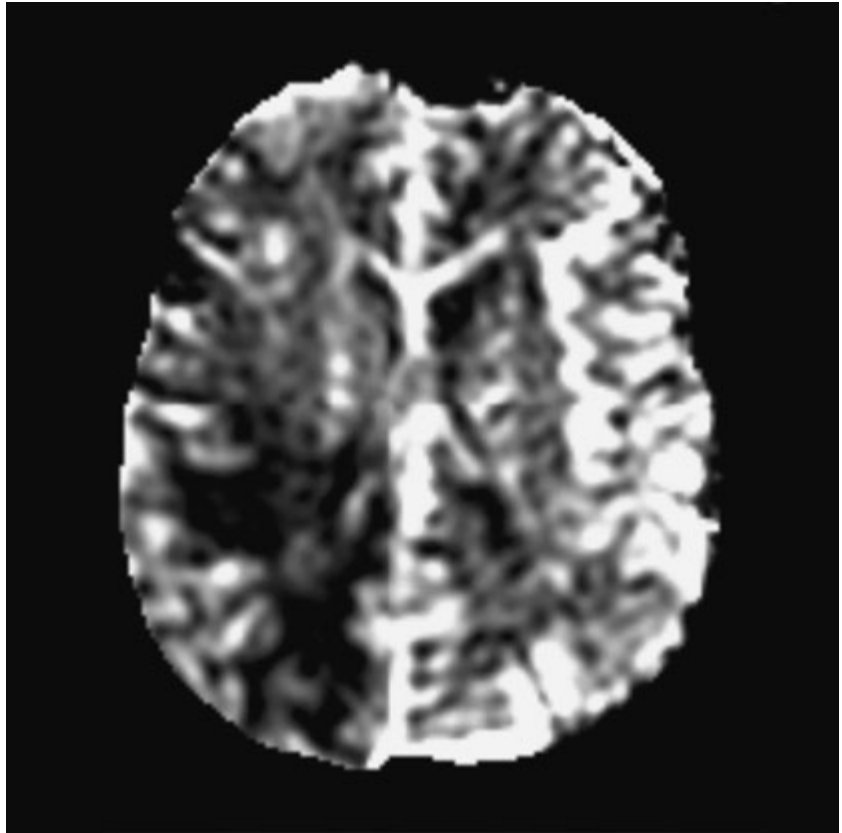
acquired as part of a dual echo acquisition or separately. TRs in the order of 3500 ms or higher are usually employed in T2 weighted FSE imaging. For PD weighted images of the brain, however, such a high TR is not optimal. If the TR is increased above 2000 ms, signal intensity of CSF increases due to reduced saturation and the high proton density of CSF. This may reduce contrast between some peri-ventricular lesions such as MS and CSF.

Blurring may be more prominent with the long ETL traditionally associated with T2 weighted FSE. A short ETL and TE are required for PD weighting to minimize T2 effects, whereas a long ETL and TE are required for T2 contrast. Blurring increases the longer the train of echoes goes out in time. Due to T2 dephasing, the echoes that occur a long way out in the train have lower signal amplitude than those at the beginning of the train. If the effective TE does not coincide with these late echoes, data from them are mapped into the resolution lines of K space and result in blurring. The echo spacing is also important as, if the echo spacing is long the final echoes in the train will occur much later in time, and therefore be of lower signal intensity than if the spacing is short, even in a train containing a relatively small number of echoes. Conversely, if the echo

spacing is short, the final echoes are collected earlier in time and will be of higher signal intensity, even in a train containing a larger number of echoes. (Note: The term 'echo train length' refers to the number of echoes collected rather than the time taken to do so). The exact method of controlling the echo spacing varies from vendor to vendor. Faster switching gradients (i.e. higher slew rates) allow for a long ETL with tight echo spacing. Generally speaking, the echo spacing should be kept as low as possible to minimize blurring.

As a result of these limitations, some advocate acquiring the PD and T2 weighted images separately as this permits the use of a shorter TR and ETL in the PD acquisition. Alternatively some vendors allow the echo train to be split in dual echo FSE acquisitions so that the PD weighted image is acquired from the first echoes in the train and the T2 weighted image from the later echoes in the train. This results in more optimal weighting for both images but note that in FSE, unlike CSE, the acquisition time for PD images is shorter than that for T2 or dual echo. This is because a TR of 2000 ms is used rather than 10 000 ms. There is therefore a time-saving to be made when only PD weighting is required. In CSE in the interests of reducing scan time, T2 weighted images already have a relatively short TR. PD and T2 weighted images therefore have similar acquisition times and are routinely acquired simultaneously in a dual echo sequence. There is therefore no time-saving to be made by acquiring PD weighted images on their own.

Despite the time advantages of using FSE in the brain, the multiple 180° pulses in an FSE sequence reduce the sensitivity to haemorrhagic lesions. If haemorrhagic lesions are suspected, a coherent gradient echo sequence may be acquired in addition to the regular sequences. It should also be noted that in many institutions, T2-FLAIR images have replaced PD-weighted images in the brain.

Due to the relatively high SNR, only a few NEX/NSA are usually required to achieve adequate image quality. However, this may not be the case when examining small structures with thin slices and/or a smaller FOV. In such a situation, it may be necessary to increase the NEX/NSA. The receive bandwidth may be decreased to increase the SNR without significantly increasing chemical shift artefact. However, generally speaking, as the receive bandwidth is reduced, the echo spacing increases and could result in an increase in FSE blurring. Rectangular FOV or parallel imaging may be utilized to reduce scan times in axial and/or coronal imaging with the phase encoding direction being R to L.

Artefact problems

The main source of artefact in the brain is from flow motion of the carotid and vertebral arteries. A spatial presaturation pulse placed I to the FOV reduces this significantly. In large FOV imaging, there is no need to place spatial presaturation pulses anywhere other than I, as there is no flow coming into the FOV from any other direction. If a small FOV is used, S or R and L spatial presaturation pulses are sometimes necessary.

8

GMN also minimizes artefact especially in the posterior fossa. However, it not only increases the signal in vessels but also the minimum TE available, and is therefore usually reserved for T2 and T2* weighted sequences. Pe gating minimizes artefact even further but, as the scan time is dependent on the patient's heart rate, it is rather time-consuming and is not therefore commonly used. Ghosting occurs along the phase encoding axis, which may be swapped in order to remove the artefact away from the ROI. However, in most examinations of the brain, this strategy is unnecessary as flow suppression techniques are satisfactory.

Uncooperative patients are likely to cause motion artefacts unless very rapid sequences are employed. FSE, while faster than SE, often produces more severe motion artefacts because one of the central lines of K space is being filled during each TR period. SS-FSE techniques greatly reduce the effects of motion and allow the whole brain to be examined in approximately 30 s by using an ETL as high as 128. SS-FSE sequences, although very rapid, may still show some degree of patient motion. In order to eliminate the effect of patient motion completely, SS-EPI techniques should be used. However, EPI sequences are prone to air/tissue magnetic susceptibility artefact (see *Pulse sequences* in Part 1*).

Patient considerations

Claustrophobia is often troublesome because of the enclosing nature of the head coil. In addition, neurological factors may increase the likelihood of patient movement. Examples of these are epilepsy, Parkinson's disease and reduced awareness or consciousness. Reassurance, and in extreme circumstances sedation or general anaesthesia, is sometimes required (see *Paediatric imaging* later in Part 2*). Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment. EPI sequences employ very rapid gradient rise times. The faster the rise times, the greater the chance for inducing peripheral nerve stimulation. To reduce this probability, the frequency encoding direction should be R to L for all axial EPI sequences in the brain. This is not necessary with SS-FSE sequences. Additionally, patients should be instructed to place their arms by their sides and to not cross their ankles to prevent creating a loop that could precipitate excessive induction of current.

Contrast usage

Contrast has several uses in standard brain imaging. It is usually required for tumour assessment such as meningiomas and neuromas. Active MS plaques and metastases also enhance, especially after high dosage. Infectious processes, such as abscesses, are very susceptible to enhancement. In addition, the meninges enhance so that infectious tuberculosis, leptomeningeal tumour spread, and post-trauma meningeal irritation can be visualized. Contrast is also used to ascertain the age of an infarct. Very recent infarcts may enhance to some degree, but maximum response to

contrast usually occurs after the blood–brain barrier has been breached. Old or chronic infarcts do not enhance. Either SE or incoherent (spoiled) GRE T1 are the sequences of choice after contrast. If a 3D incoherent (spoiled) GRE sequence is acquired using isotropic voxels, the dataset may be reformatted in other planes and/or slice locations. Perfusion imaging, with a rapidly infused bolus of gadolinium, is useful for measuring the activity of a lesion. In these cases rapid acquisitions such as SS-FSE or EPI are required.

8

Temporal lobes

Basic anatomy (Figure 8.21)
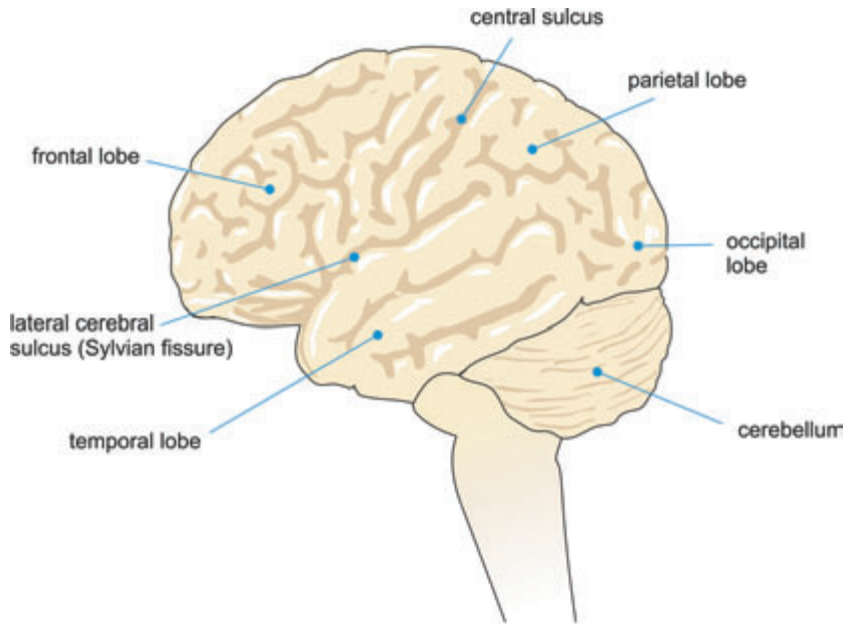
Figure 8.21 The temporal lobe and its relationships.

Common indications

- Diagnosis and evaluation of a lesion specifically in the temporal lobes (tumours, vascular malformations, leukodystrophies and atrophic processes).
- Temporal lobe epilepsy.
- Evaluation of signal change in the hippocampus and the temporal lobe
- Measurement of the hippocampal volume (hippocampal atrophy is presently considered the most sensitive indicator of hippocampal disease especially in Alzheimer's disease and schizophrenia).

Equipment

- Head coil (quadrature, or multi-coil array).
- Immobilization pads and straps.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the interpupillary line is parallel

to the couch and the head is straight. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the nasion. Straps and foam pads are used for immobilization.

Suggested protocol

Sagittal SE T1

Medium slices/gap are prescribed on either side of the longitudinal alignment light through the whole head. The area from the foramen magnum to the top of the head is included in the image.

L 37 mm to R 37 mm

Axial/oblique SE/FSE T2

Thin slices/gap or interleaved are angled parallel to the temporal lobe that can be seen on a lateral slice on the sagittal images (Figure 8.22). Prescribe the slices from the inferior aspect of the temporal lobes to the superior border of the body of the corpus callosum.

8
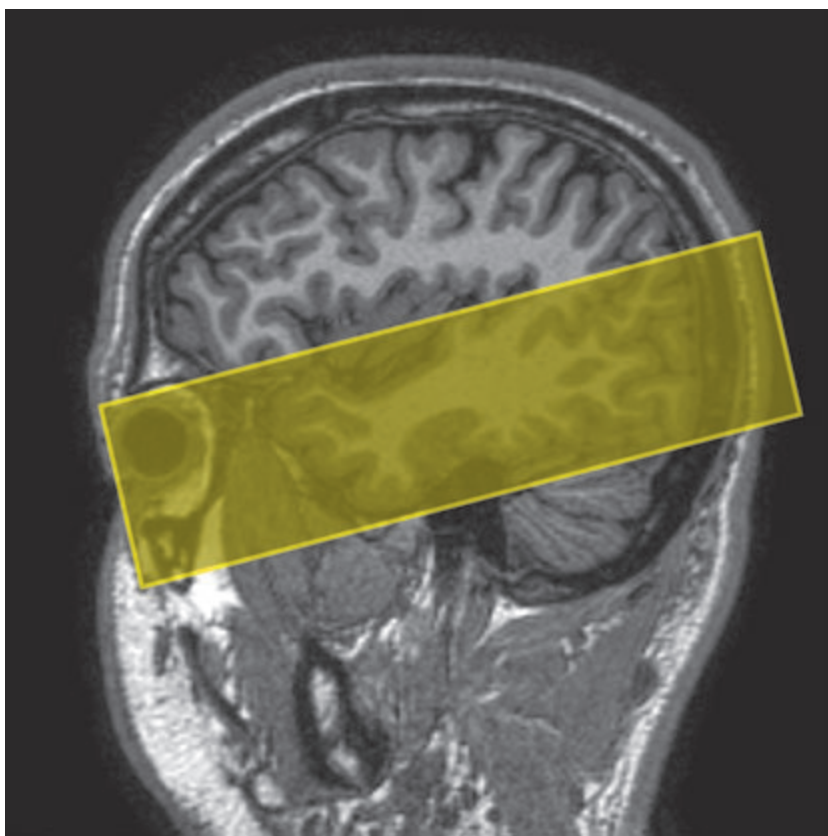
Figure 8.22 Sagittal SE T1 weighted image through a temporal lobe showing slice prescriptions boundaries and orientation for axial/oblique imaging of the temporal lobes.

Figure 8.23 Sagittal SE T1 weighted image through a temporal lobe showing slice prescription boundaries and orientation for coronal/oblique imaging of the temporal lobes.

8
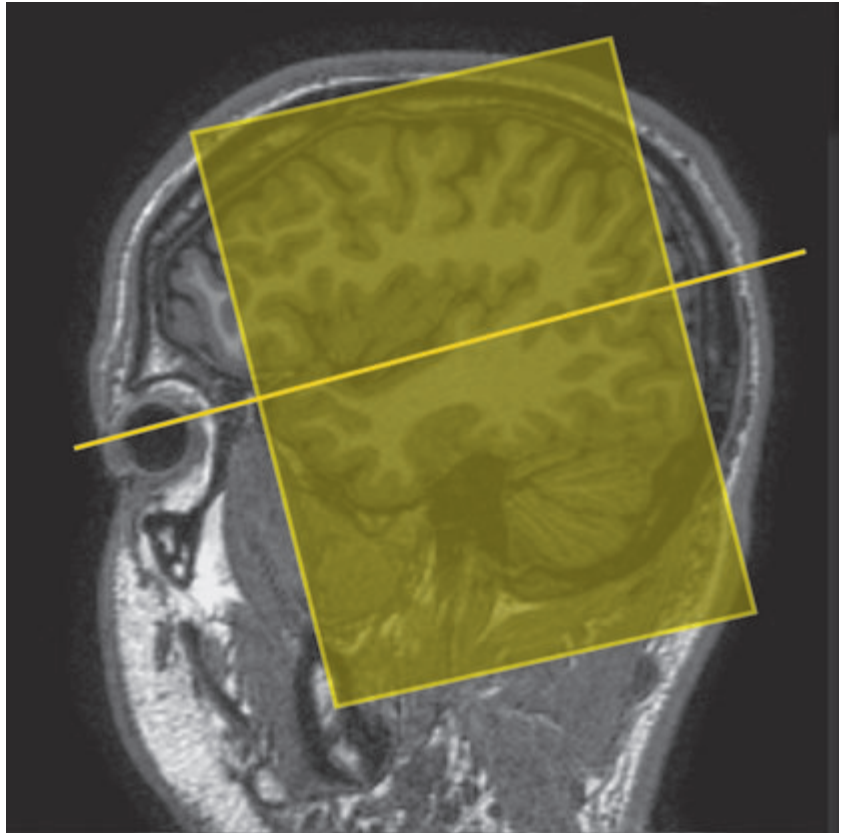
Coronal/oblique SE/FSE T1

As for the Axial/oblique T2, **except** thin slices interleaved are angled perpendicular to the axials (Figure 8.23).

Slices are prescribed from the posterior portion of the cerebellum to the anterior border of the genu of the corpus callosum.

Coronal 3D incoherent (spoiled) GRE T1 (Figure 8.24)

Thin slices are either prescribed through the temporal lobes only (medium number of slice locations), or the whole head (large number of slice locations). For hippocampal measurements, slices are prescribed from the posterior portion of the cerebellum to the anterior border of the genu of the corpus callosum. Hippocampal volumes are measured by using system software to calculate the area of the hippocampus on each slice and multiplying this by the depth of the slice slab. If reformatting of slices is desired, then an isotropic dataset should be acquired (see *Volume imaging* under *Parameters and trade-offs* in Part 1).
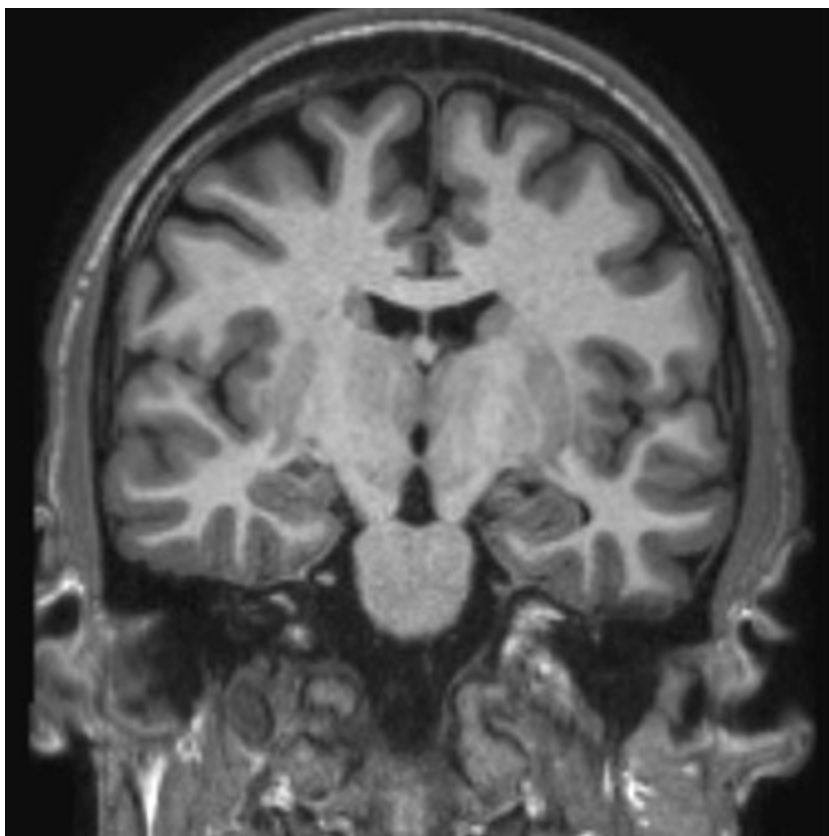
Figure 8.24 Coronal incoherent (spoiled) T1 weighted GRE image through the hippocampi acquired as part of a 3D acquisition.

Axial/oblique/Coronal/oblique IR-FSE T2 (Figures 8.25 and 8.26)

Slice prescription as for Axial/oblique/Coronal/oblique FSE T2.

This sequence often provides images with high contrast between grey matter and white matter. A TI selected to null the signal from white matter (about 300 ms) can be used to increase the grey/white contrast in the hippocampal region. Images may be video-inverted so that white matter appears white and the grey matter appears grey. This is sometimes useful to increase the conspicuity of white matter lesions, which have a low signal intensity when using this technique.

Image optimization

Technical issues

The SNR and contrast characteristics of the temporal lobes are usually excellent as the quadrature head coil and phased array coil yield high and uniform signal. Good spatial resolution is therefore achievable in

Figure 8.25 Axial IR-FSE T2 weighted image with a TI selected to null the signal from white matter (300 ms).
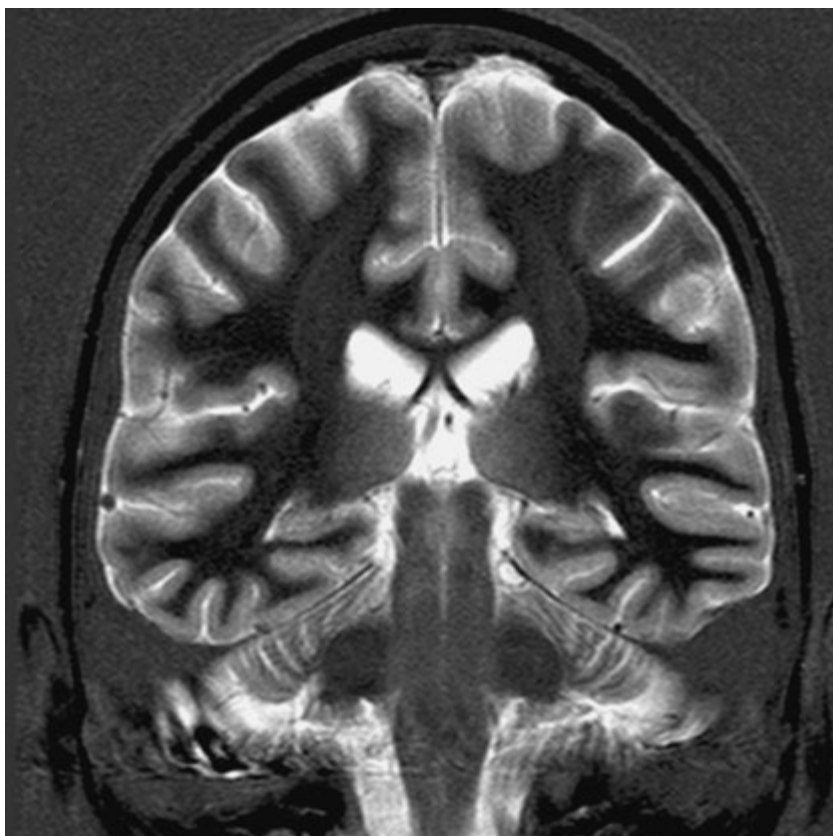
Figure 8.26 Axial IR-FSE T2 weighted image video inverted to better demonstrate white matter lesions.
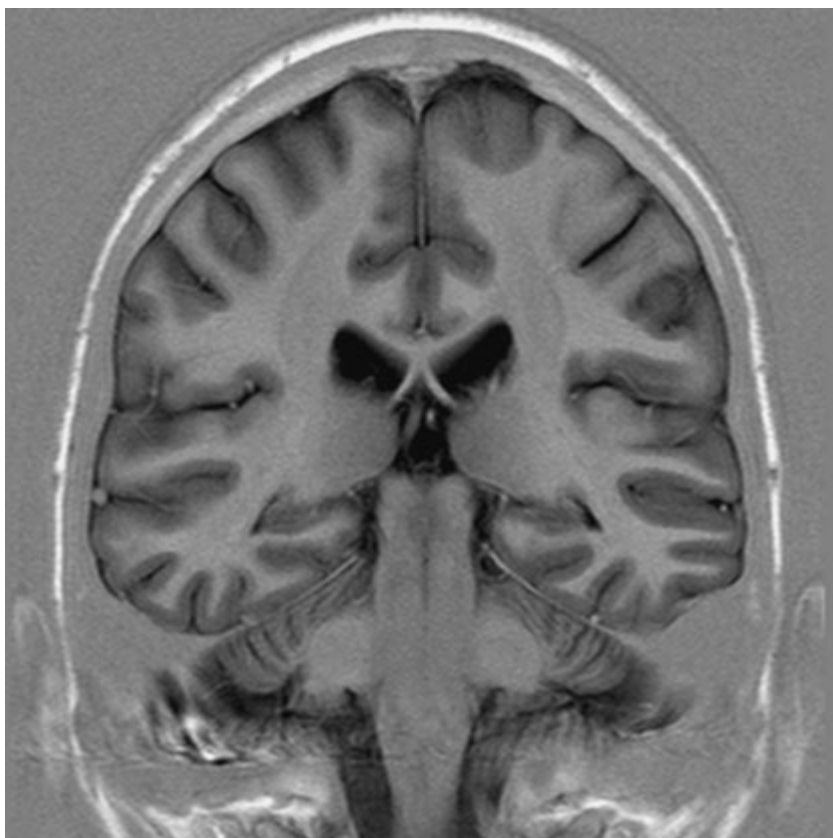
relatively short scan times. Surface coils placed directly on the patient's head increase local SNR and resolution, especially in children. However, using this method, other areas of the brain cannot be imaged due to signal fall-off. As lesions within the temporal lobes are often quite small, volume acquisitions are useful as they allow for very thin slices and no gap. As they are mainly utilized to demonstrate anatomy or contrast enhancement, an incoherent (spoiled) GRE that produces PD and T1 contrast is desirable. Alternatively, angling the slices perpendicular to the sylvian fissure in 2D acquisitions often improves visualization of the temporal lobes.

FSE is a useful pulse sequence especially for T2 weighted images, as FSE in conjunction with fine matrices acquires high-resolution images of the temporal lobes in a relatively short scan time. However, IR sequences can also be utilized to great effect. FLAIR sequences usually demonstrate subtle areas of increased T2 signal intensity better than T2 weighted SE or FSE sequences. As the brain contains no fat (only small amounts occur in the scalp), reducing the receive bandwidth significantly improves the SNR without significantly increasing chemical shift artefact, although there may be increased blurring (see *Flow phenomena and artefacts* in Part 1). A rectangular/asymmetric FOV can be effectively used to reduce scan times in axial and coronal imaging with the phase axis R to L.

Artefact problems

The main source of artefact in the temporal lobes is from flow motion of the carotid and vertebral arteries. A spatial presaturation pulse placed I to the FOV reduces this significantly. In large FOV imaging, there is no need to place spatial presaturation pulses anywhere other than I, as there is no flow coming into the FOV from any other direction. On coronal images, phase artefact from the carotid and vertebral vessels is often troublesome. Swapping the phase axis so that it lies S to I instead of R to L removes artefact away from the laterally situated temporal lobes, but oversampling is necessary to prevent the neck and the top of the head wrapping into the FOV along the phase axis. This method of swapping the phase direction is used most effectively to reduce artefact in the lateral portion of the temporal lobes. However, phase ghosting can still interfere with the more medially situated hippocampi, and if they are the ROI there is probably no benefit in swapping the phase axis.

GMN also minimizes artefact in the temporal lobes. However, it not only increases the signal in vessels but also the minimum TE available, and is therefore usually reserved for T2 and T2* weighted sequences. Magnetic susceptibility is often seen at high field strengths on the coronal incoherent (spoiled) GRE images, especially at the border of the petrous ridge and the brain. If slices are prescribed through the temporal lobe only, spatial presaturation pulses are brought into the FOV in the volume acquisition to reduce aliasing along the slice select axis (see *Volume imaging* under *Parameters and trade-offs* in Part 1*).*

8

Patient considerations

Claustrophobia is often troublesome because of the enclosing nature of the head coil. Careful explanation of the procedure and reassurance is necessary. As many of these patients have drug-resistant epilepsy, careful observation of the patient throughout the examination is important. The gradient noise and bore and alignment lights are potential sources of epileptic stimuli. If the patient fits during the examination stop scanning immediately, withdraw the patient from the magnet, call a physician and instigate first-aid measures. Owing to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is sometimes helpful to demonstrate small lesions in the temporal lobes.

8

Posterior fossa and internal auditory meati

Basic anatomy (Figure 8.27)
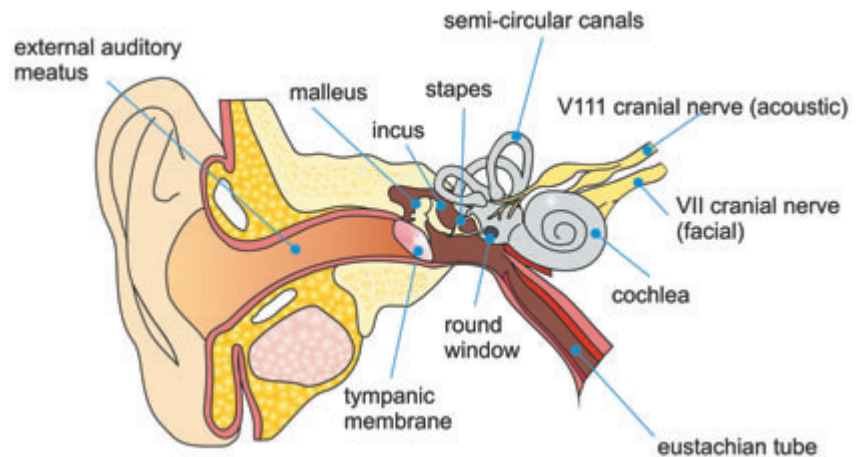
Figure 8.27 The anatomy of the inner ear.

Common indications

- Symptoms that require the exclusion of an acoustic neuroma (vertigo, unilateral sensory hearing loss, tinnitis).
- Facial palsy/numbness.
- Diagnosis of a posterior fossa lesion.
- Hemifacial spasm.
- Trigeminal neuralgia.

Equipment

- Head coil (quadrature or multi-coil array).
- Immobilization pads and straps.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the interpupillary line is parallel to the couch and the head is straight. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the nasion. Straps and foam pads are used for immobilization.

Figure 8.28 Sagittal SE T1 weighted midline slice through the brain showing slice prescription boundaries and orientation for axial imaging of the internal auditory meatus (IAM).

8
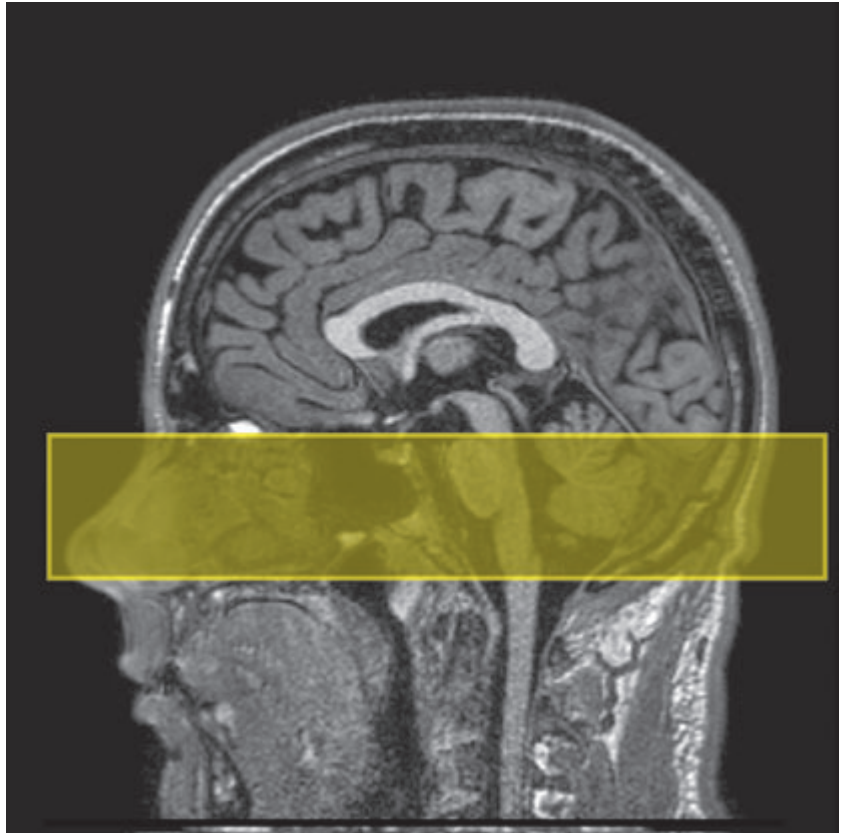
Suggested protocol

Sagittal SE T1 or coherent GRE T2* (Figure 8.28)

Medium slices/gap are prescribed either on each side of the longitudinal alignment light, or through the internal auditory meatus (IAM) on one side only. The area from the foramen magnum to the superior border of the body of the corpus callosum is included in the image.

L 37 mm to L 20 mm (left IAM)
R 37 mm to R 20 mm (right IAM)

Axial SE/FSE T1 (Figure 8.29)

Thin slices/gap or interleaved are prescribed through the posterior fossa from the foramen magnum to the superior border of the petrous ridge. Coverage is increased if a large posterior fossa tumour is present.

Axial SE/FSE T1 with contrast

Slice prescription as for Axial T1.

Figure 8.29 Axial SE T1 weighted image through the internal auditory meati (IAM).

8

Additional sequences

Coronal SE/FSE T1 +/– contrast

As for Axial T1, **except** slices are prescribed from the posterior border of the cerebellum to the clivus (Figure 8.30).

3D incoherent (spoiled) GRE T1 +/– contrast

Thin slices and a small or medium number of slice locations are prescribed to cover the area as above (axially or coronally).

High-resolution technique

Axial FSE T2 (Figure 8.31).
  Slices prescribed as for Axial T1.

8

Thin slices/gap or interleaved	3 mm
Long TE	100 ms
Long TR	4000 ms
Long ETL	16
Matrix	512×256 or greater
NEX/NSA	4
FOV	20 cm

Coronal

As for Axial high resolution T2, **except** prescribe slices from the posterior border of the cerebellum to the clivus.

3D FSE T2 or GRE T2* (Figure 8.32)

This sequence produces images with high contrast and SNR. Additionally, the images are contiguous and will not suffer from cross-excitation. An isotropic acquisition allows multiplanar reformatting (see *Volume imaging* under *Parameters and trade-offs* in Part 1). GRE sequences such
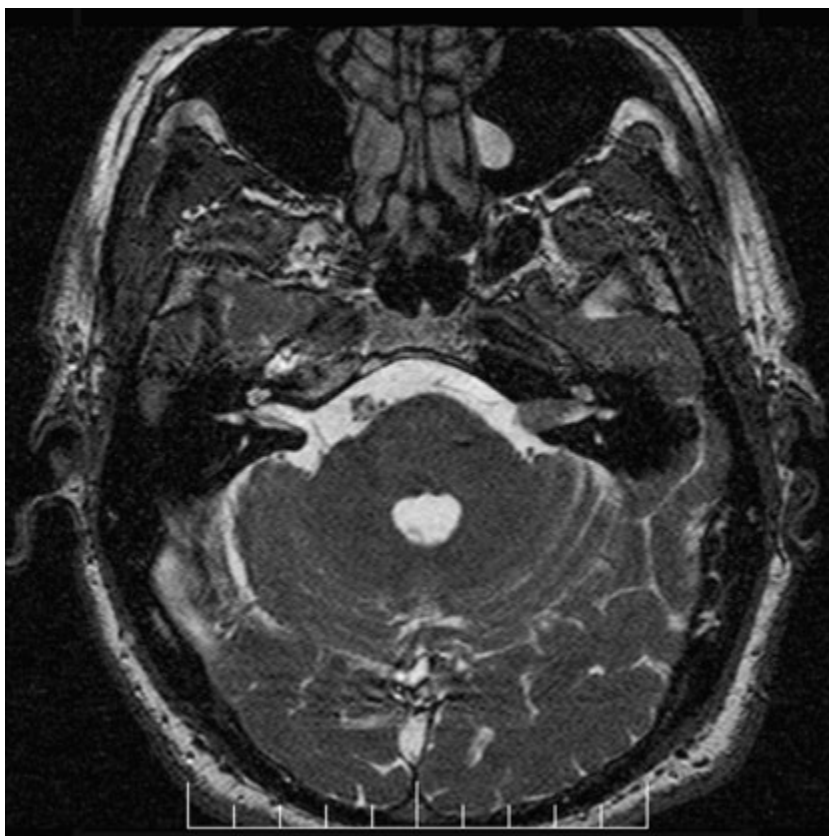
Figure 8.31 Axial FSE T2 weighted high resolution image of the internal auditory meati (IAM).

as balanced gradient echo are commonly used as flow artefacts from the posterior fossa are reduced.

Image optimization

Technical issues

The IAM are very small structures and this examination is usually carried out to exclude a small acoustic neuroma situated within the canal. Therefore it is important to achieve the highest spatial resolution possible in keeping with good SNR. The inherent SNR is usually excellent due to the high proton density of the brain tissue and the quality of the head coil. However, in the region of the IAM, the low proton density of the petrous bones and mastoids reduces the SNR. The thinnest slices and smallest gap or interleaving are used to optimize spatial resolution and visualization of the IAM. A very fine matrix is advisable, although increasing this too much can reduce the SNR to unacceptable levels. To optimize spatial

Figure 8.32 Axial FSE T2 weighted high resolution image of the internal auditory meati (IAM) demonstrating a large left acoustic neuroma. This examination did not require contrast to confirm the diagnosis.
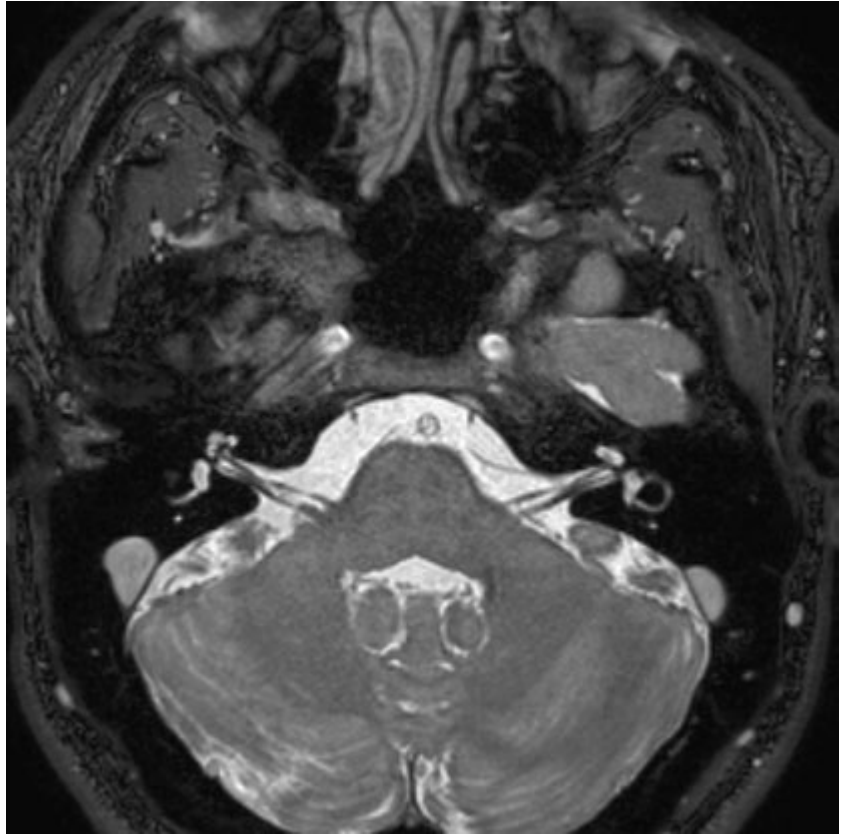
resolution even further, the FOV is reduced compared with standard brain imaging. As a result of all these measures, the NEX/NSA may have to be increased to maintain SNR.

A high-resolution T2 FSE technique usually negates the use of contrast enhancement and the T1 sequence, especially when examining the IAM. When FSE is used in conjunction with matrices of at least 512, extremely good resolution and contrast are achievable. The T2 weighting of the sequence produces excellent contrast between the high signal of the CSF and the relatively low signal of the nerve. The fine matrix gives very good resolution of many of the cranial nerves and vessels in the posterior fossa. The facial and auditory nerves can usually be seen as distinct from each other within the canal, and under these circumstances contrast may not be necessary. The NEX/NSA is increased to maintain the SNR, but the scan times are still only in the order of a few minutes due to the implementation of FSE. However, at lower field strengths more NEX/NSA are usually required to achieve satisfactory SNR. This sequence is also useful in the coronal plane when looking specifically at the posterior fossa.

Volume acquisitions eliminate the slice gap and enable very thin slices to be acquired. Incoherent (spoiled) GRE sequences after contrast

enhancement are common, but heavily T2 weighted acquisitions using FSE or GRE are often superior. Magnetization prepared sequences may also be of value. If the whole of the posterior fossa is under examination, spatial resolution may not be as important as with the IAM. If the ROI is large (such as a tumour invading the fossa) slightly thicker slices/gap are employed, and a routine brain protocol is often required.

Artefact problems

Flow motion from the venous sinuses is often troublesome in the posterior fossa. GMN minimizes this artefact but it not only increases the signal in vessels but also the minimum TE available, and is therefore reserved for T2 weighted sequences. Spatial presaturation pulses placed S and I to the FOV are also beneficial. Pe gating reduces artefact even further but, as the scan time is dependent on the patient's heart rate, it is sometimes rather time-consuming. The implementation of Pe gating is, therefore, best reserved for cases of severe flow artefact that cannot be reduced to tolerable levels by other measures. The use of balanced gradient echo also reduces flow artefact due to use of the balanced gradient system and short TE and TR (see *Pulse sequences* in Part 1).

Patient considerations

Claustrophobia is sometimes troublesome because of the enclosing nature of the head coil, and patients are often very deaf and may not respond to the system intercom. Under these circumstances, careful explanation and reassurance of the patient are important. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

8

Contrast usage

As T1 weighted sequences yield low inherent contrast between the petrous ridge and the IAM and acoustic neuromas demonstrate good enhancement, contrast is usually necessary. However, the high-resolution technique and/or the 3D FSE sequence often diagnoses or rules out an acoustic neuroma without contrast.

Pituitary fossa

Basic anatomy (Figure 8.33)
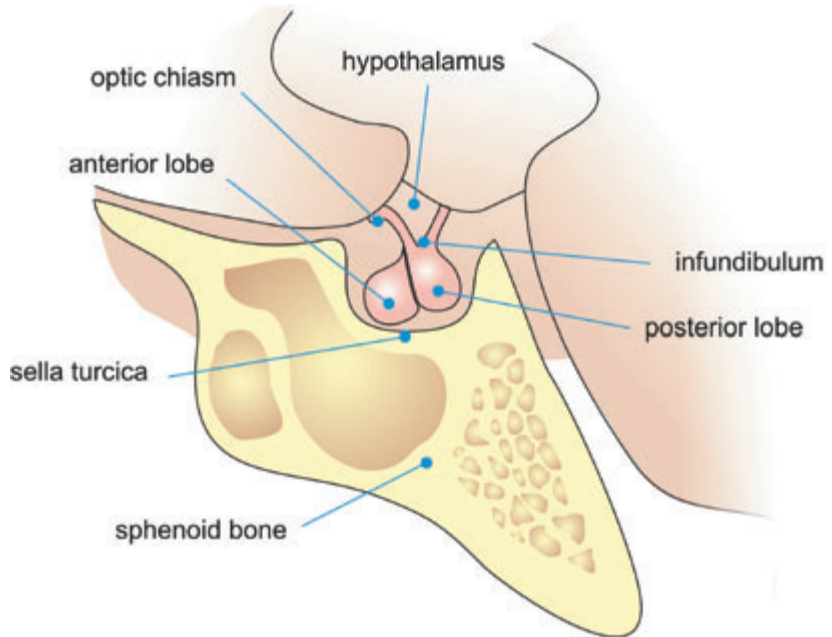
Figure 8.33 The components of the pituitary gland.

Common indications

- Investigation of diseases related to pituitary function (hyperprolactinaemia, Cushing's disease, acromegaly, hypopituitarism, diabetes insipidus, amenorrhoea).
- Hypothalamic disorders.
- Visual field defect.
- Post-operative assessment of pituitary adenomas.

Equipment

- Head coil (quadrature or multi-coil array).
- Immobilization pads and straps.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the interpupillary line is parallel
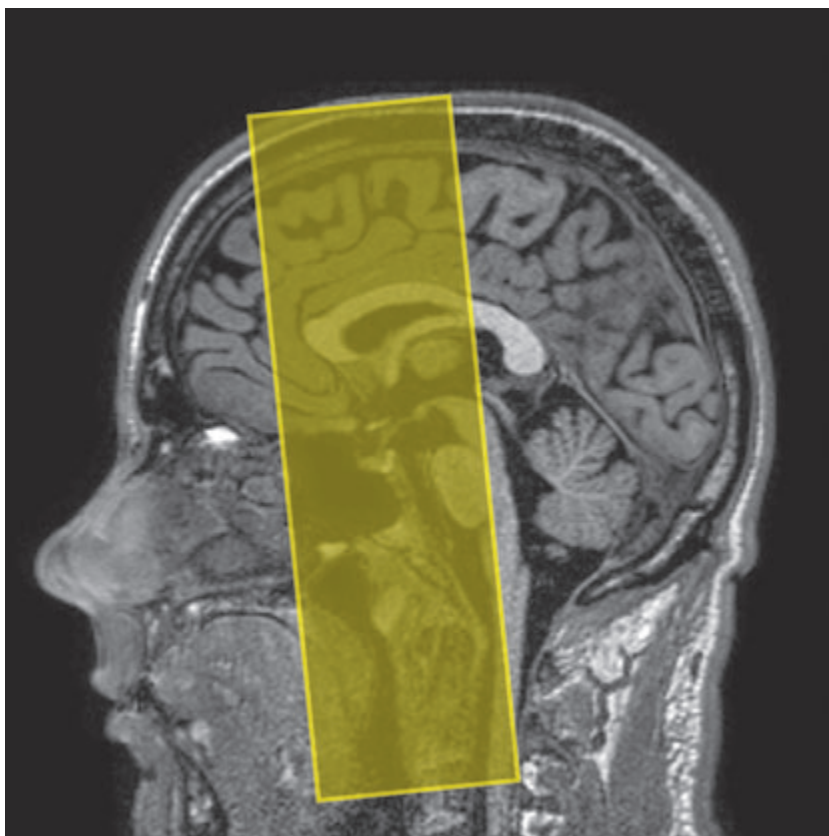
Figure 8.34 Sagittal SE T1 weighted midline slice through the brain showing slice prescription boundaries and orientation for coronal imaging of the pituitary fossa.

to the couch and the head is straight. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the nasion. Straps and foam pads are used for immobilization.

Suggested protocol

Sagittal SE T1 (Figure 8.34)

Thin slices/gap or interleaved are prescribed from the left to the right lateral borders of the pituitary fossa. The area from the inferior edge of the sphenoid sinus to the superior portion of the lateral ventricles is included in the image.

L 10 mm to R 10 mm

Coronal SE/FSE T1 (Figure 8.35)

Thin slices/gap or interleaved are prescribed from the posterior clinoids to the anterior clinoids. The inferior border of the sphenoid sinus to the
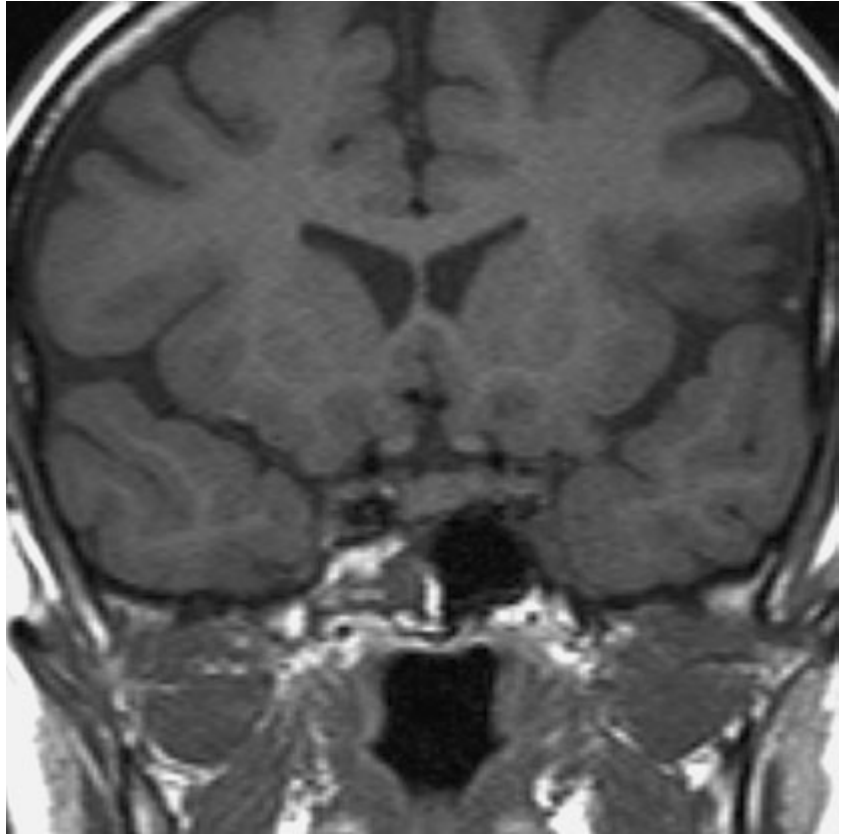
Figure 8.35   Coronal FSE T1 weighted image through the pituitary fossa.

superior portion of the lateral ventricles is included in the image. Use chemical/spectral presaturation if a high signal mass is seen to exclude intrasellar dermoid.

Additional sequences

Coronal SE/FSE T1 + contrast

Slice prescription as for Coronal T1 without contrast.

Sagittal SE/FSE T1 +/− contrast

Slice prescription as for Sagittal T1 without contrast.

3D incoherent (spoiled) GRE T1 +/− contrast

Thin slices and a small number of slice locations are prescribed through the pituitary fossa. Extend coverage anteriorly and posteriorly to allow for slice wrap.
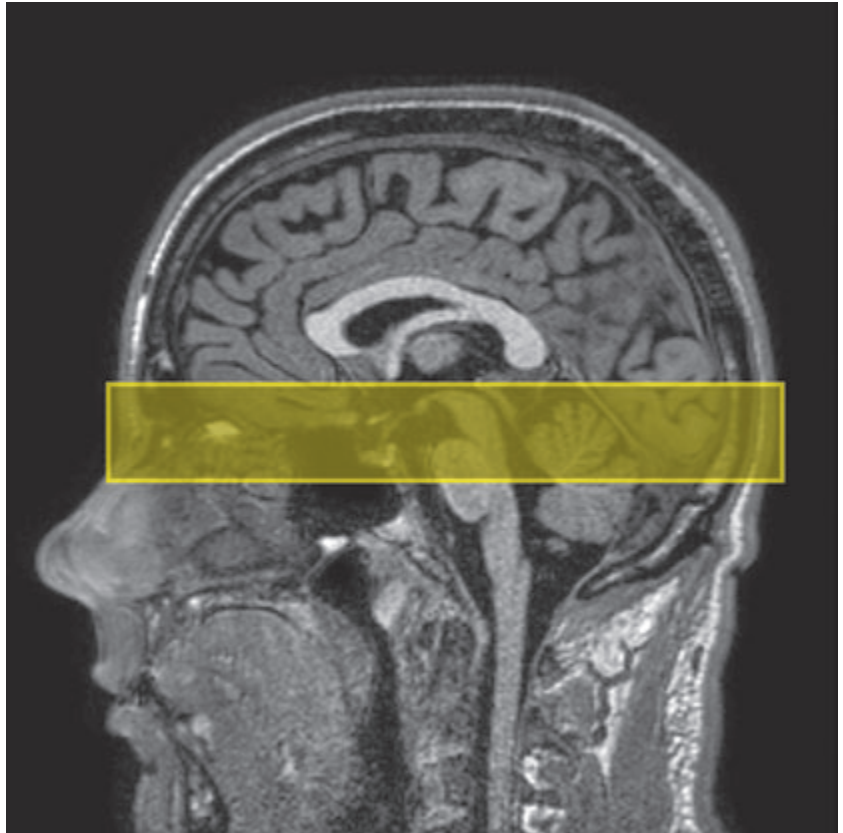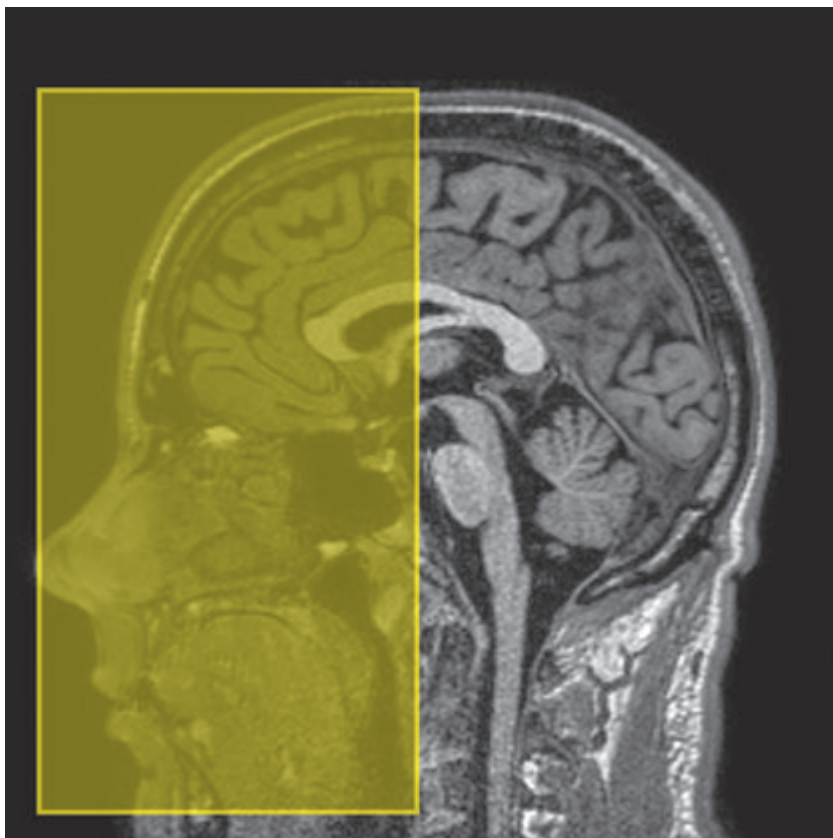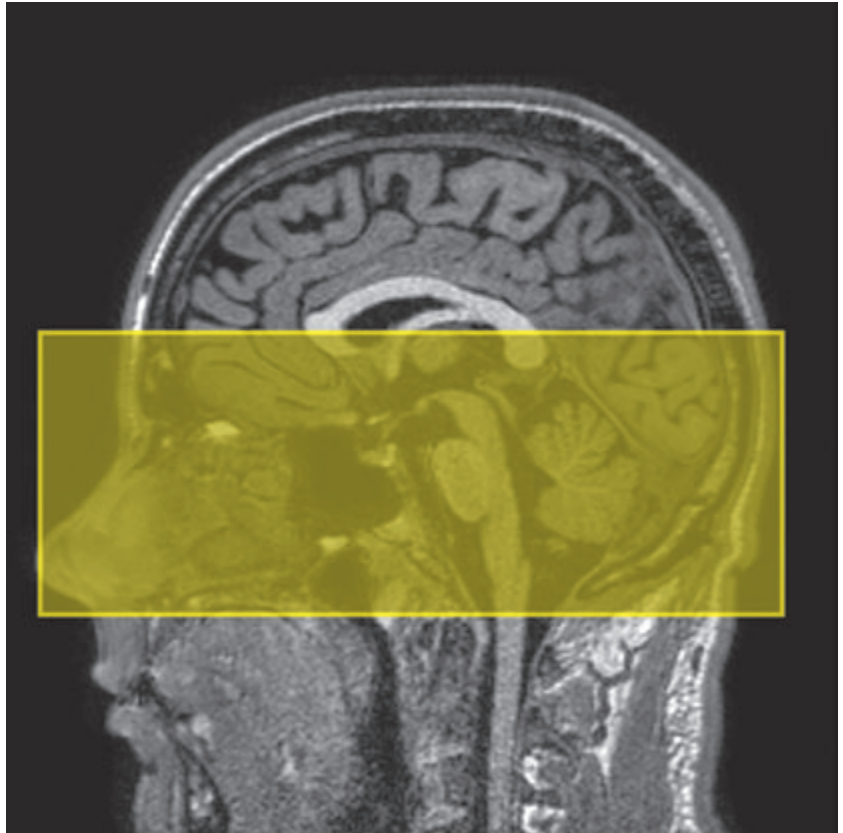
Figure 8.36 Sagittal SE T1 weighted midline slice through the brain showing slice prescription boundaries and orientation for axial imaging of the pituitary fossa.

8

Axial SE/FSE T1 +/− contrast

As for Coronal T1, **except** slices prescribed from the floor of the pituitary fossa to the circle of Willis (Figure 8.36).

Image optimization

Technical issues

The pituitary fossa is a relatively small structure and, in addition, micro-adenomas are often difficult to visualize. As a result spatial resolution is important. To optimize this use thin slices interleaved and the smallest FOV possible in keeping with good SNR. In addition, a fine matrix used in conjunction with multiple NEX/NSA is necessary to maintain SNR. Volume acquisitions allow for thinner slices and no gap and are therefore sometimes useful in this area. As anatomical detail and contrast enhancement are important, an incoherent (spoiled) GRE sequence is required.

Artefact problems

The pituitary fossa is located just anterior and inferior to the circle of Willis and therefore flow artefact is often more troublesome than in standard brain imaging. In addition, the smaller FOV increases the likelihood of aliasing, so oversampling is necessary if anatomy exists outside the FOV in the phase direction. Spatial presaturation bands are placed S, I, and L and R of the FOV to reduce artefact and aliasing, but this often increases the SAR so that the slice number available per TR decreases. In extreme circumstances Pe gating may be required but, as the scan time depends on the proficiency of gating and the patient's heart rate, scan times are often considerably lengthened.

In volume acquisitions only a small slice slab is required and, therefore, slice wrap is usually troublesome. When prescribing slices always increase coverage to compensate for this. Spatial presaturation bands placed A and P to the edges of the slice slab help to reduce aliasing of this type (see *Flow phenomena and artefacts* in Part 1). GMN minimizes flow artefact in the pituitary region; however, it not only increases the signal in vessels but also the minimum TE available, and is therefore not usually beneficial in T1 weighed sequences. Incoherent (spoiled) GRE sequences through the pituitary fossa may suffer from excessive magnetic susceptibility artefacts when acquired on high field systems (1.0 T and above). Lower field strengths, however, can benefit from the increased SNR provided by 3D acquisitions while taking advantage of reduced magnetic susceptibility artefacts.

Patient considerations

Claustrophobia is often troublesome due to the enclosing nature of the head coil. Careful explanation of the procedure and reassurance are required to avoid the necessity of sedation. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely required except for diabetes insipidus and hypothalamic disorders. Contrast is sometimes necessary for Cushing's disease because micro-adenomas are often very small, and not seen on unenhanced scans. However, it should be noted that eventually all the pituitary gland enhances as well as the microadenoma itself, and therefore careful timing of post-contrast scans is important. It is common to see a high signal intensity in the posterior lobe of the pituitary on unenhanced images, especially in patients with diabetes. At present, the causes and clinical significance of this have not been fully evaluated. In addition, studies have shown that half-dose gadolinium may be optimal for imaging the pituitary.

Orbits

Basic anatomy (Figure 8.37)
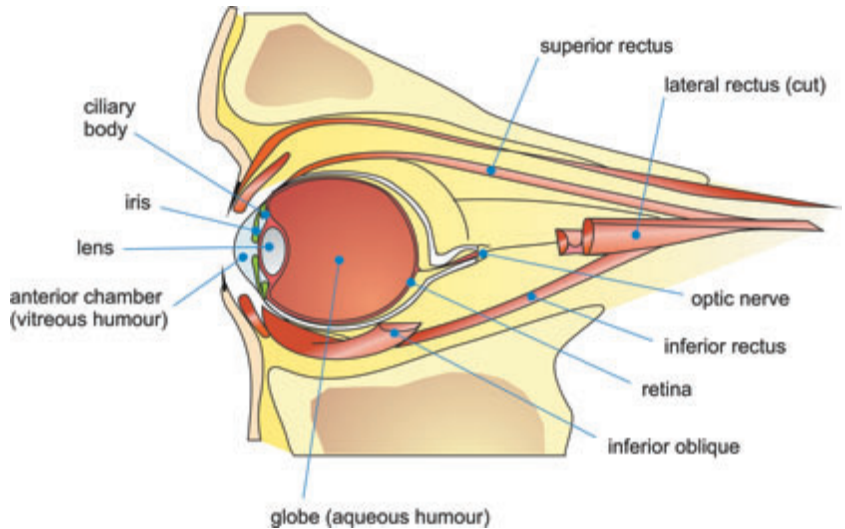
Figure 8.37 The structures of the orbit in sagittal section.

Common indications

- Proptosis.
- Visual disturbance.
- Evaluation of orbital or ocular mass lesions.

Equipment

- Small surface coil for globe and orbit.
- Quadrature head coil or multi-coil array coil for orbital apex, chiasm and intracranial optic pathways.
- Immobilization straps and foam pads.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch. Both orbits are usually examined at the same time. If surface coils are used, these are placed over each orbit but should not touch the patient. Special holders are often provided by the manufacturers to enable the coils to be placed anteriorly

over the eyes. Ensure that the receiving side of the coils faces the orbits, i.e. towards the table. The patient assumes a fixed gaze, straight ahead, with the eyes open. This enables the patient to focus and keeps the eyes still, thereby reducing motion artefact. Any eye make-up is removed prior to the examination as this causes image artefact and patient discomfort, especially if it contains metal.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the orbits. If surface coils are used, this corresponds to the centre of the coils. Straps and foam pads are used for immobilization.

Suggested protocol

Sagittal SE/FSE T1

Medium slices/gap are prescribed on either side of the longitudinal alignment light through the whole head. The area from the foramen magnum to the top of the head is included in the image.

L 37 mm to R 37 mm

Axial/oblique SE/FSE T1 or T2 (Figure 8.40)

Thin slices/gap or interleaved are prescribed either in the true axial plane, or angled to the optic nerve from the inferior margin of the orbit to above the chiasm (Figures 8.38 and 8.39).

Coronal SE/FSE T2 or STIR

As for Axial/oblique T1, **except** prescribe slices from the posterior border of the globe to the posterior aspect of the chiasm. Use chemical/spectral presaturation on SE/FSE sequences (Figure 8.41).

Additional sequences

Coronal/Axial SE/FSE T1

As for Axial/Coronal above, **except** use contrast and chemical/spectral presaturation.

If optic neuritis is suspected, scan the whole brain.

Image optimization

Technical issues

If surface coils are used, the SNR in the region of the globe and the anterior aspect of the orbit is high. This allows for excellent spatial resolution

Figure 8.38 Sagittal SE T1 weighted image of the orbit and optic nerve showing the correct orientation of axial/oblique slices parallel to the optic nerve.
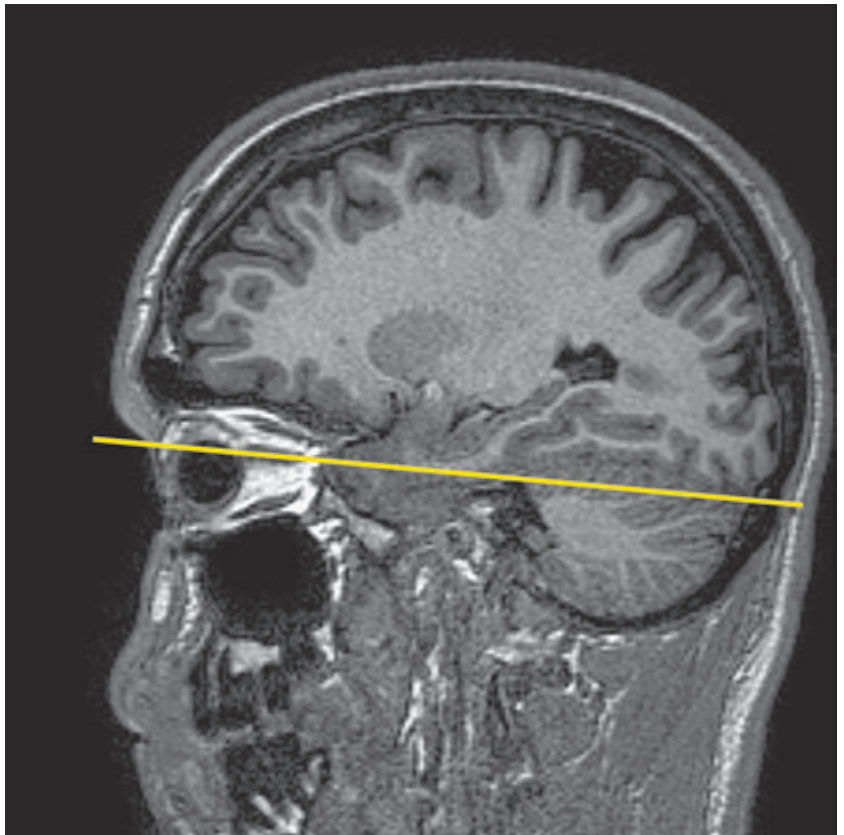
Figure 8.39 Sagittal SE T1 weighted slice through the orbit showing slice prescription boundaries and orientation for axial/oblique imaging of the orbits and optic nerve.

8
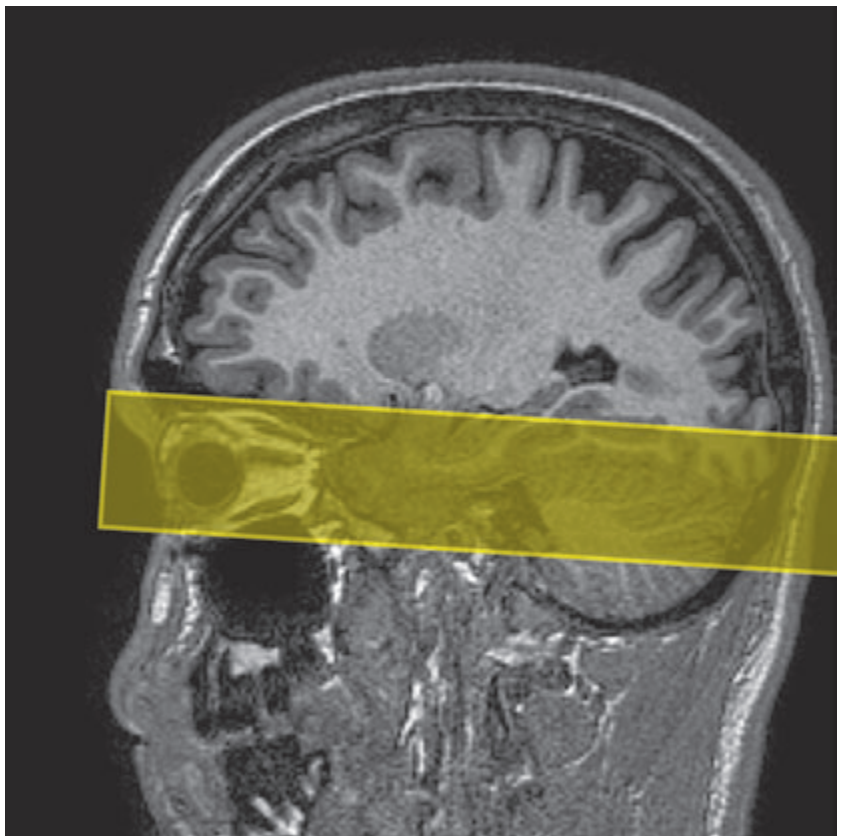
Figure 8.40 Axial/oblique FSE T2 of the orbits clearly demonstrating the lens of the eye, the globe, the optic nerves and the chiasm.
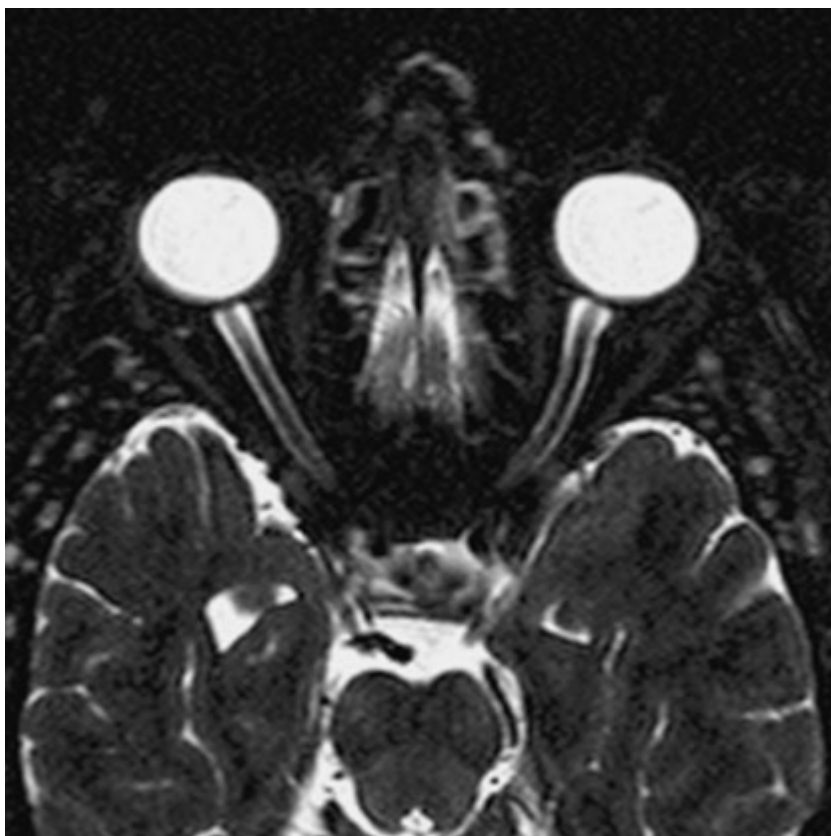
Figure 8.41 Sagittal SE T1 weighted slice through the orbits showing slice prescription boundaries and orientation for coronal imaging of the orbits and optic nerve.
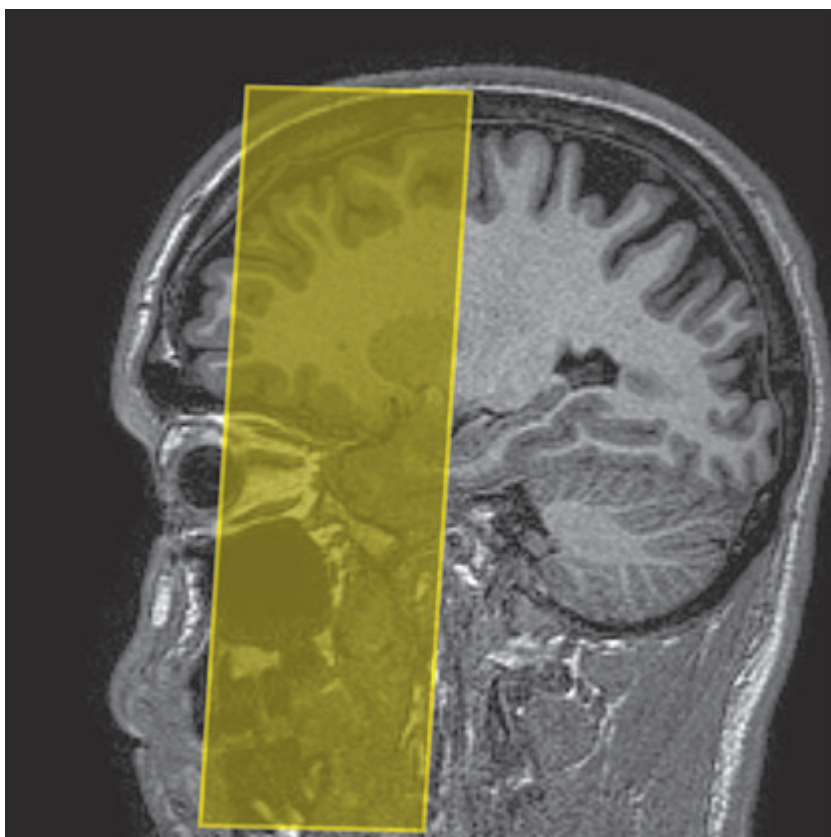
of small structures such as the optic nerve, but there is signal fall-off at the orbital apex. Therefore the choice of coil largely depends on the coverage required. If the globe, the retro-orbital area and the portion of the optic nerve within the orbit are of interest, a surface coil is the best choice. If, however, information about the chiasm and intracranial optic pathways is required, the head coil is necessary. Thin interleaved slices or a very small gap are needed to obtain the resolution within the orbit and chiasm. Fine matrices and a small FOV are also required to maintain resolution, and therefore multiple NEX/NSA are necessary to preserve SNR.

FSE is probably the ideal sequence, especially for T2 weighted images, as speed is important due to motion artefact from blinking and eye movement. Due to the high fat content within the orbit, chemical/spectral presaturation/STIR are often necessary to visualize orbital structures adequately. This is especially true on the FSE T2 sequences, where fat returns a signal similar to the CSF surrounding the optic nerve.

Artefact problems

The main source of artefact is from eye movement. Instruct the patient to focus on the roof of the bore of the magnet and to blink as little as possible. Use the fastest sequence possible in keeping with good contrast, resolution and SNR. FSE is a valuable pulse sequence in achieving this. Flow motion in the Circle of Willis is often troublesome in the chiasm, which lies just beneath it. Use spatial presaturation bands placed S and P to the FOV to reduce this. In addition, spatial presaturation bands placed I to the FOV reduce flow motion from the carotids. GMN also minimizes flow motion but, as it increases the signal in vessels and the minimum TE, it is usually reserved for the T2 weighted sequences.

As a small FOV is commonly used in this area, aliasing is a problem especially if the head coil is employed, because tissue outside the FOV in the phase axis produces signal. Oversampling is therefore required to eliminate this. If any magnetic susceptibility artefact is seen, especially superiorly to the orbit, this may be due to eye make-up left on the eyelid. This must be totally removed prior to the examination. Chemical shift artefact can occur on high field strength systems due to the presence of intra-orbital fat. Fat suppression techniques reduce this and if they are used, the receive bandwidth can be reduced to increase the SNR. Additional shimming may be required before chemical/spectral presaturation sequences.

Patient considerations

Some patients may be blind or partially sighted and consideration should be given to this. The patient is carefully instructed on the importance of keeping the eyes still. Focusing is practised before the examination and the patient told when, during the examination, blinking is undesirable and when it is allowed. Obviously if the patient is blind, focusing is not possible and so the technique is adapted to ensure that the sequences are

8

as fast as possible. All eye make-up must be removed prior to the examination to avoid artefact and to reduce discomfort, as some make-up can heat up during the examination. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is valuable in assessing the optic nerve and chiasm as well as intra-orbital masses. However, due to the presence of orbital fat, the administration of contrast only serves to increase the signal of these structures so that they are isointense with fat on T1 weighted images. Therefore some means of suppressing the fat signal is required when using contrast enhancement. It is important to note that STIR cannot be used for this purpose, as contrast decreases the T1 recovery time of the tissue so that it is similar to that of fat. Therefore, the inverting pulse used in STIR sequences sometimes nullifies the signal from enhancing tissues as well as fat. If fat suppression is required use chemical/spectral presaturation.

Paranasal sinuses

Basic anatomy (Figure 8.42)
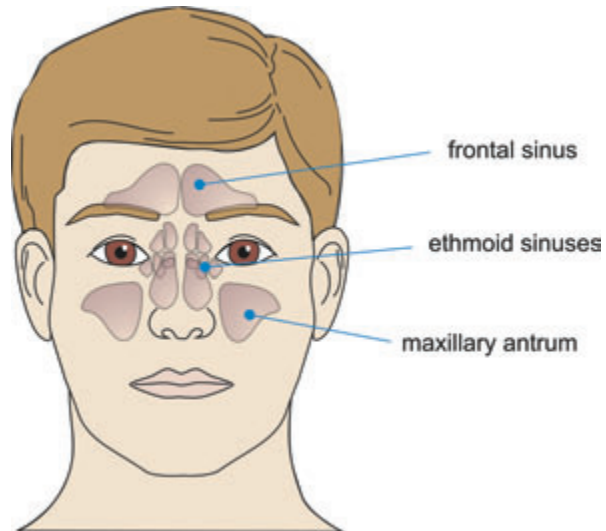
Figure 8.42   Anterior view of the paranasal sinuses.

Common indications

- Staging of neoplasms prior to resection.
- Distinction of inflammation from neoplasm.

Equipment

- Head coil (quadrature or multi-coil array).
- Immobilization foam pads and straps.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the interpupillary line is parallel to the couch and the head is straight. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the nasion. Straps and foam pads are used for immobilization.

Suggested protocol

Sagittal SE T1

Medium slices/gap are prescribed on either side of the longitudinal alignment light through the whole head. The area from the foramen magnum to the top of the head is included in the image.

L 37 mm to R 37 mm

Coronal SE/FSE T1

Medium slices/gap are prescribed from the posterior portion of the sphenoid sinus to the tip of the nose. All of the paranasal sinuses are included in the image from the inferior margin of the maxillary sinuses to the superior border of the frontal sinuses (Figure 8.43).

Axial SE/FSE T1

As for Coronal T1, **except** prescribe slices from the inferior border of the maxillary sinuses to the superior edge of the frontal sinuses (Figure 8.44).


Figure 8.43   Sagittal SE T1 weighted midline slice through the brain showing slice prescription boundaries and orientation for coronal imaging of the paranasal sinuses.

Figure 8.44 Sagittal SE T1 weighted midline slice through the brain showing slice prescription boundaries and orientation for axial imaging of the paranasal sinuses.

8

Coronal/Axial SE/FSE PD/T2

Slice prescription as for Axial and Coronal T1.

Additional sequences

The use of MR to image the sinuses has recently extended into interventional procedures. The use of open magnet systems that allow near real-time imaging has proved beneficial in functional endoscopic sinus surgery. The multiplanar capabilities of MR enable rapid visualization of the optic nerve in three planes so that this type of surgery has become safer and quicker.

Image optimization

Technical issues

The SNR and CNR of the sinuses are often poor due to the low proton density of the air-filled cavities. MRI does not demonstrate bony resolution

as well as computer tomography (CT), but it is useful for visualizing the nature and extent of soft tissue masses. Spatial resolution is not usually as important as good SNR in this region. Medium slices are selected to maintain SNR, and multiple NEX/NSA are employed as long as the scan time is kept within reasonable limits. The use of FSE enables the implementation of fine matrices and multiple NEX/NSA whilst maintaining relatively short scan times.

Artefact problems

The main source of artefact is from the carotid, vertebral and jugular vessels. The use of spatial presaturation pulses placed I to the FOV usually reduces this to acceptable levels. GMN may be employed but, as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. On the axial and coronal images, phase artefact occurs in the R to L direction, which may obscure the maxillary sinuses. However, the strategy of swapping the phase direction places this artefact S and I, which can then interfere with the frontal, ethmoid and sphenoid sinuses. Under these circumstances, swapping the phase axis rarely has merits unless the maxillary sinuses are under examination and flow artefact is a particular problem. If the phase axis is swapped on the coronal images, oversampling is necessary to prevent wrap from the neck and top of the head. Magnetic susceptibility artefact from dental fillings sometimes interferes with the maxillary sinuses but is not easily remedied, other than to avoid GRE sequences.

Patient considerations

Claustrophobia is often troublesome because of the enclosing nature of the head coil. Under these circumstances reassurance and a careful explanation of the procedure is required. Some patients may have profuse nasal secretions so that they need to swallow or blow their nose frequently during the examination.

Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast enhances the mucous lining of the sinuses but it is not commonly used for sinus disease. It is, however, useful to distinguish between enhancing tumour and non-enhancing effusion.

Pharynx

Basic anatomy (Figure 8.45)
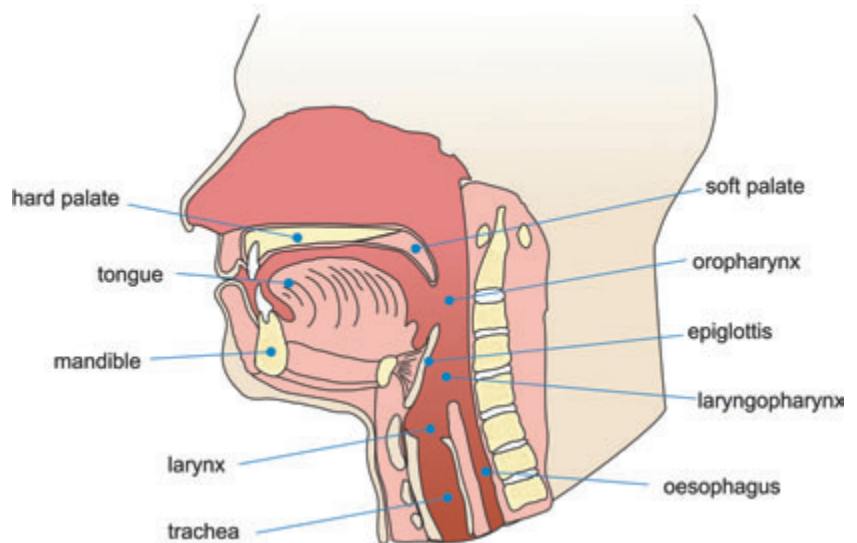
Figure 8.45   Sagittal section through the mouth and pharynx.

Common indications

- Staging of oropharyngeal carcinoma.
- Pharyngeal and parapharyngeal masses.
- Investigation of sleep apnoea.
- Swallowing disorders.

Equipment

- Anterior neck coil/volume neck coil for cervical nodal involvement.
- Head coil (quadrature or phased array) for pharyngeal area and base of skull.
- Immobilization pads and straps.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the interpupillary line is parallel to the couch and the head is straight. If the neck is to be imaged for nodal involvement, the anterior or volume neck coil is placed around or

anterior to the patient's neck. Care should be taken to include the base of the skull within the coil. The patient's head is straightened as this usually straightens the neck as well.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the angle of the jaw. When imaging the cervical nodes, the vertical alignment light should be located midway between the posterior and anterior surfaces of the neck. A soft pad may be placed under the patient's neck to facilitate this, although many dedicated coils ensure that the neck naturally assumes the correct position. Straps and foam pads are used for immobilization.

Suggested protocol

Coronal SE/FSE T1 (Figure 8.46)

Thin slices/gap are prescribed from the posterior border of the cervical cord to the anterior surface of the neck. This distance is measured relative to the vertical alignment light before the examination. The area from the skull base to the sternoclavicular joints is included in the image (Figure 8.47).

P 25 mm to A 25 mm

8
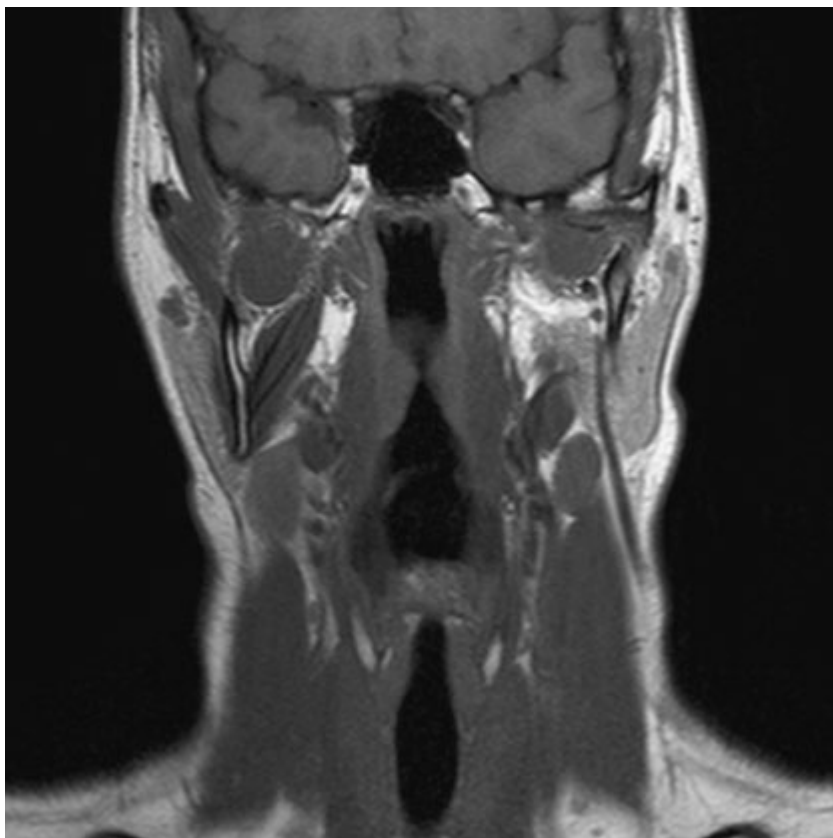
Figure 8.46   Coronal FSE T1 weighted localizer of the pharynx.
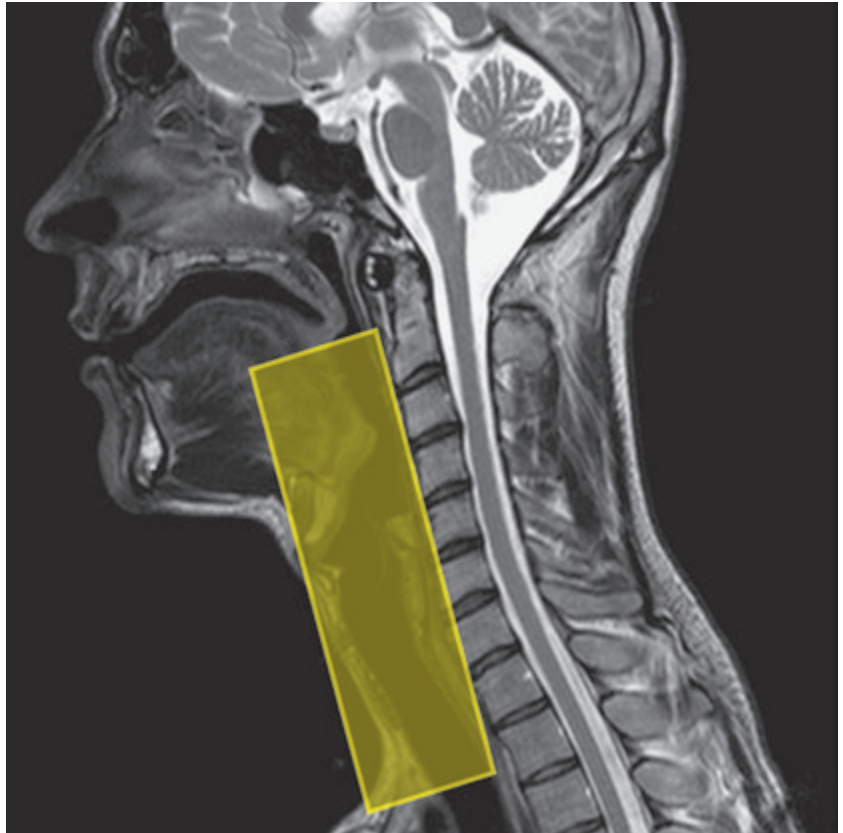
Figure 8.47   Coronal FSE T1 weighted localizer showing slice prescription boundaries and orientation for coronal imaging of the pharynx.

8

Axial SE/FSE PD/T2

Thin slices/gap are prescribed from the thyroid cartilage to the base of the skull (Figure 8.48).

Sagittal SE/FSE PD/T2

As for Axial PD/T2, **except** prescribe slices from the left to the right lateral walls of the pharynx.

The coverage is increased if nodal or parapharyngeal disease is suspected. The area from the skull base to the thyroid cartilage is included in the image (Figure 8.49).

Additional sequences

When assessing tumour spread the scan plane and slice coverage is altered depending on the site of the primary tumour as follows:

Figure 8.48 Coronal FSE T1 localizer showing slice prescription boundaries and orientation for axial imaging of the pharynx.
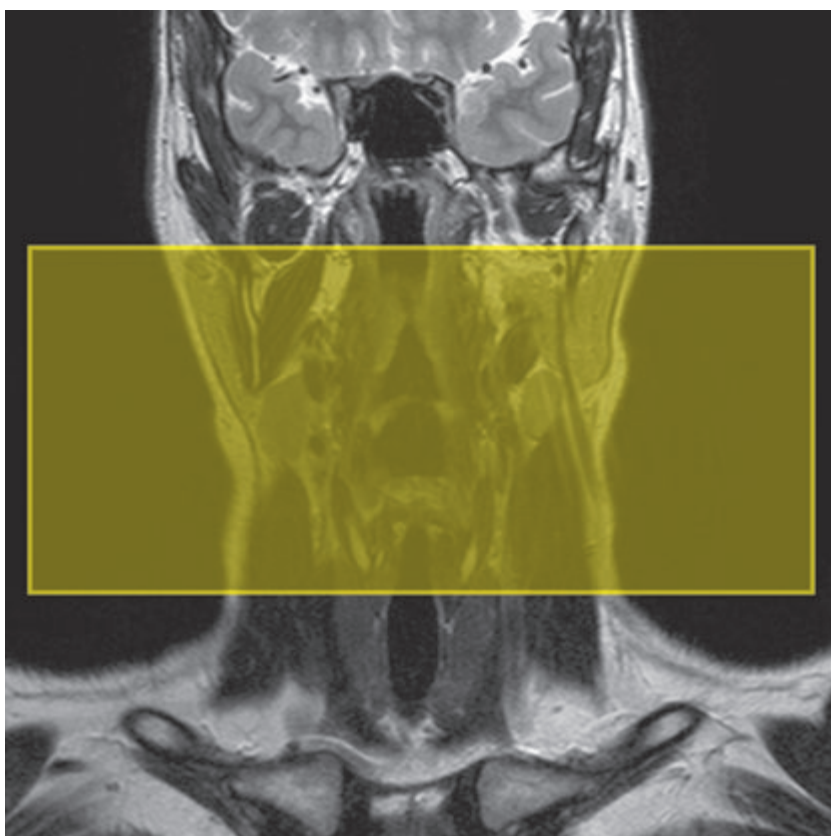
Figure 8.49 Coronal FSE T1 localizer showing slice prescription boundaries and orientation for sagittal imaging of the pharynx.
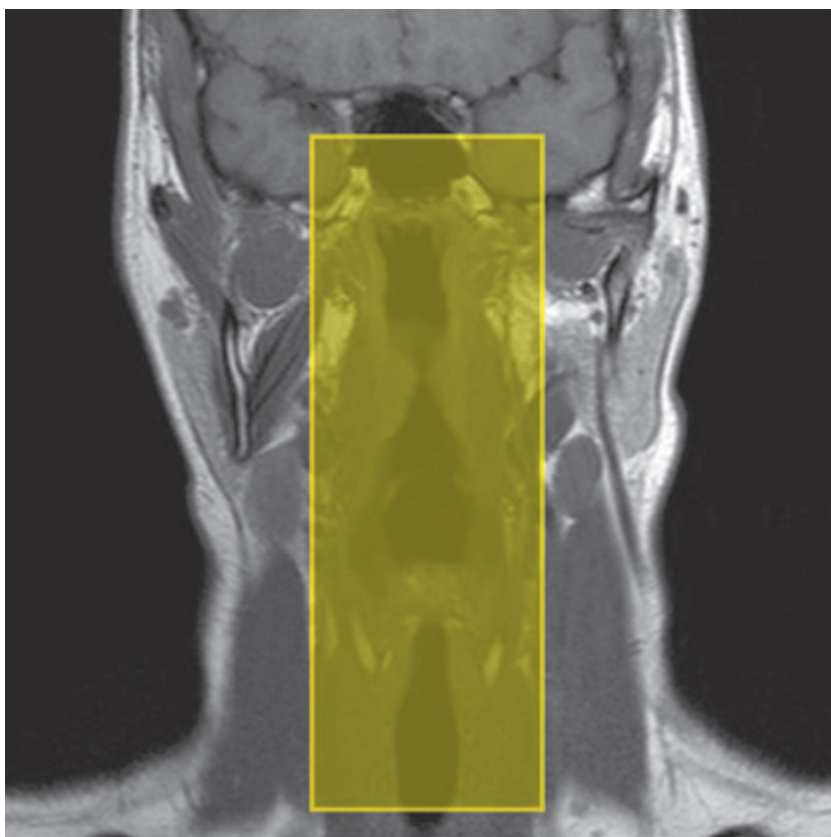
- Oral tumours include cervical nodes in the axial and coronal plane.
- Nasopharyngeal tumours include the sphenoid sinus in the sagittal and axial plane.
- Oropharyngeal tumours include the parapharyngeal space, the base of the middle cranial fossa, and the anterior triangle of the neck in the axial and coronal plane.

Rapid sequences are proving useful in dynamic imaging of the pharynx to assess swallowing. The patient is instructed to swallow bread or mashed potato soaked in gadolinium and the bolus imaged during swallowing. As the upper pharyngeal phase of swallowing is very rapid, sequences such as EPI, which can acquire 20–25 images per second, are necessary in combination with good resolution. In addition, 3D imaging of the pharynx may be utilized to assess anatomy during sleep.

Image optimization

Technical issues

The anterior portion of the neck is a notoriously difficult area to examine. The SNR is often poor, especially if a substandard coil is used. The head coil is probably the best coil for this examination, although an anterior or volume coil moulded to the face and neck is necessary to best visualize the cervical lymph nodes and inferior tumour spread. However, even with the best coils, multiple NEX/NSA are often necessary to maintain SNR. Spatial resolution is also important in this area, and therefore thin slices/gap and a fairly fine matrix are required to optimize resolution. The use of these matrices and multiple NEX/NSA often leads to long scan times.

A solution to these problems is to use FSE in conjunction with a rectangular/asymmetric FOV. FSE reduces the scan time significantly and yields higher SNR, especially on the T2 weighted sequences. A rectangular/asymmetric FOV allows the acquisition of fine matrices in shorter scan times. In coronal and axial imaging, the long axis of the rectangle is placed S to I and A to P, respectively.

Artefact problems

Artefact in this region arises from flow motion in the carotid, vertebral and jugular vessels, and from swallowing. Spatial presaturation pulses placed S and I to the FOV reduce flow artefact significantly. Bringing the spatial presaturation pulses into the FOV increases their effectiveness, but care must be taken that they do not obscure important anatomy. GMN further reduces artefact but, as it also increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences.

Swallowing is a common problem in this area. If the patient swallows too often, motion artefact interferes with the image. Using multiple NEX/NSA to average out this artefact reduces phase ghosting, but leads to longer scan times. If the patient does not swallow at all, pooling of saliva

8

in the pyriform fossae can sometimes lead to difficulties in image inter-
pretation. The patient should be advised to swallow as little as possible
during the examination but to try to clear the mouth of saliva when
they do. Respiratory motion may move the anterior neck coil during the
acquisition of data. If this is a problem, instruct the patient to breathe
shallowly. In addition, small foam pads placed between the chest and
the coil help to reduce coil movement. Magnetic susceptibility artefact
from dental fillings sometimes interferes with important anatomy but is
not easily remedied, other than to avoid GRE sequences.

Patient considerations

Some patients with oral or pharyngeal pathology produce copious saliva
and have difficulty swallowing. This often leads to choking or major
swallowing artefact. Try to calm and reassure the patient as much as
possible before the examination. Give the patient plenty of tissues and, in
extreme circumstances, consider examining the patient prone. The patient
is instructed to swallow as little as possible during the examination but to
ensure that they clear the mouth of saliva when they do. This prevents
saliva pooling in the pyriform fossae.

 Due to excessively loud gradient noise associated with some sequences,
ear plugs must always be provided to prevent hearing impairment.

8

Contrast usage

This is rarely indicated but may be useful to distinguish the extent or
nature of a lesion.

Larynx

Basic anatomy (see Figure 8.45)

Common indications

- Carcinoma of the larynx.
- Assessment prior to reconstruction of the larynx.
- Disorders of the vocal cords and phonation.

Equipment

- Anterior neck coil/volume neck coil.
- Immobilization foam pads and straps.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch. The coil is placed around or anterior to the patient's neck. The patient's head is straightened as this usually straightens the neck as well. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the thyroid cartilage (Adam's apple). The vertical alignment light should be located midway between the posterior and anterior surfaces of the neck. A soft pad may be placed under the patient's neck to facilitate this, although many dedicated coils ensure that the neck naturally assumes the correct position. Straps and foam pads are used for immobilization.

8

Suggested protocol

Sagittal SE/FSE T1/T2 (Figure 8.50)

Thin slices/gap are prescribed on either side of the longitudinal alignment light from the left to the right lateral skin surfaces of the neck. The area from the superior border of the hard palate to the sternoclavicular joints is included in the image.

L 25 mm to R 25 mm

Axial SE/FSE T1

Thin slices/gap are prescribed through the laryngeal cartilages and vocal cords (Figure 8.50). The slices may be angled parallel to the larynx for tumours limited to the cords.

Figure 8.50   Sagittal FSE T2 weighted image through the neck showing slice prescription boundaries and orientation for axial imaging of the larynx.
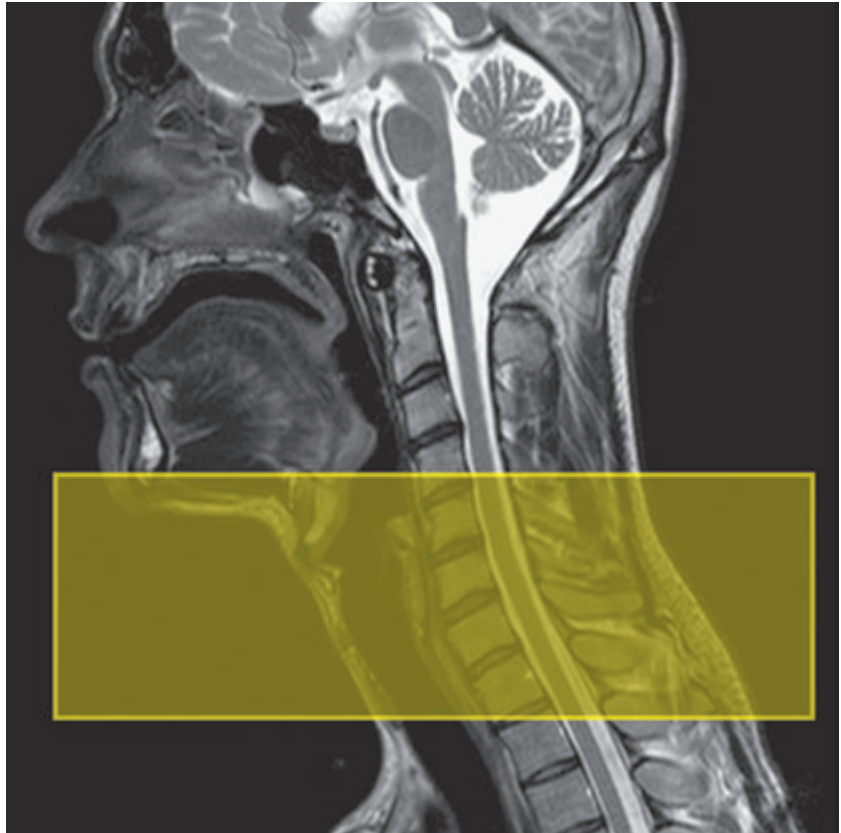
Coronal SE/FSE T1

As for the Axial T1, **except** prescribe slices from posterior surface of the trachea to anterior surface of the neck.

The slices may be angled so that they are parallel to the larynx for tumours limited to the vocal cords (Figure 8.51). The area from the superior border of the hard palate to the sternoclavicular joints is included in the image.

Axial/Coronal SE/FSE PD/T2

Slice prescription as for SE/FSE T1. Useful to distinguish advanced tumour from muscles and the thyroid gland.

Additional sequences

Fast incoherent (spoiled) GRE/EPI T1

During phonation to assess function of the vocal cords.
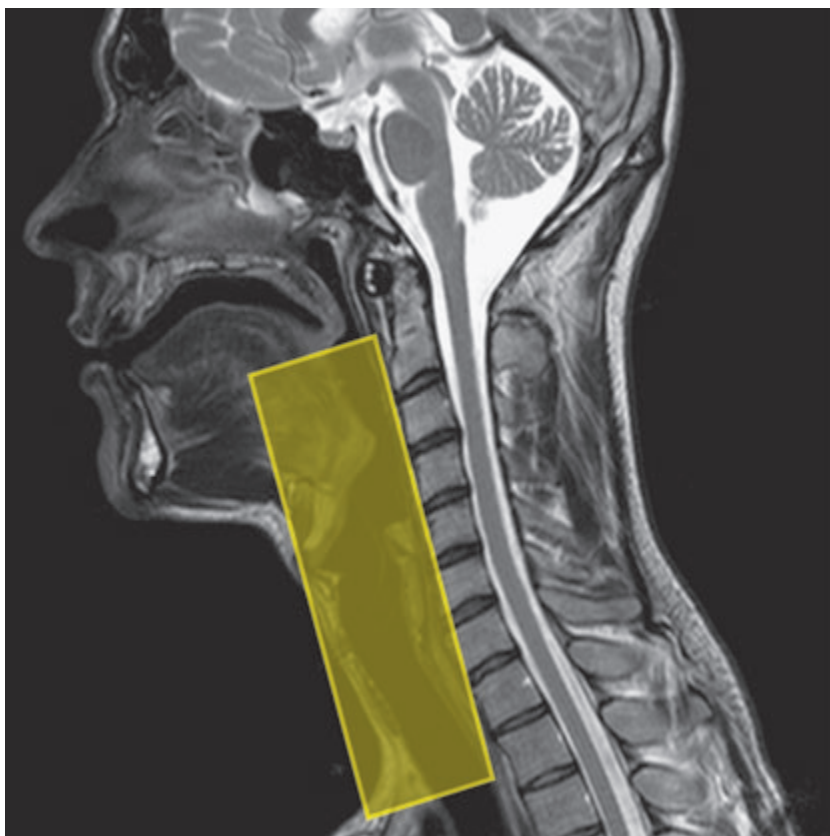
Figure 8.51 Sagittal FSE T2 weighted image through the neck showing slice prescription boundaries and orientation for coronal/oblique imaging of the larynx.

8

Image optimization

Technical issues

The anterior portion of the neck is a notoriously difficult area to examine. The SNR is often poor, especially if a substandard coil is used. An anterior neck coil moulded to the face and neck is probably the best coil for this examination. However, even with these coils, multiple NEX/NSA are often necessary to maintain SNR. Spatial resolution is also important in this area, and therefore thin slices/gap and a fairly fine matrix are required to optimize resolution. The use of these matrices and multiple NEX/NSA often leads to long scan times.

A possible solution to these problems is to use FSE in conjunction with a rectangular/asymmetric FOV. FSE reduces the scan time significantly and yields higher SNR, especially on the T2 weighted sequences. A rectangular/asymmetric FOV allows the acquisition of fine matrices in shorter scan times. In coronal and axial imaging, the long axis of the rectangle is placed S to I and A to P, respectively.

Artefact problems

Artefact in this region arises from flow motion in the carotid, vertebral and jugular vessels, and from swallowing. Spatial presaturation pulses placed S and I to the FOV reduce flow artefact significantly. Bringing the spatial presaturation pulses into the FOV increases their effectiveness but care must be taken that they do not obscure important anatomy. GMN further reduces artefact but, as it also increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences.

The patient should be advised to swallow as little as possible during the examination. The implementation of multiple NEX/NSA averages out any phase ghosting but leads to longer scan times. Respiratory motion may move the anterior neck coil during the acquisition of data. If this is a problem, instruct the patient to breathe shallowly. In addition, small foam pads placed between the chest and the coil help to reduce coil movement.

Patient considerations

A careful explanation of the procedure and the importance of minimizing swallowing during the examination is important. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

8

Contrast usage

This is rarely indicated but may be useful to distinguish the extent or nature of a lesion.

Thyroid and parathyroid glands

Basic anatomy (Figures 8.52 and 8.53)
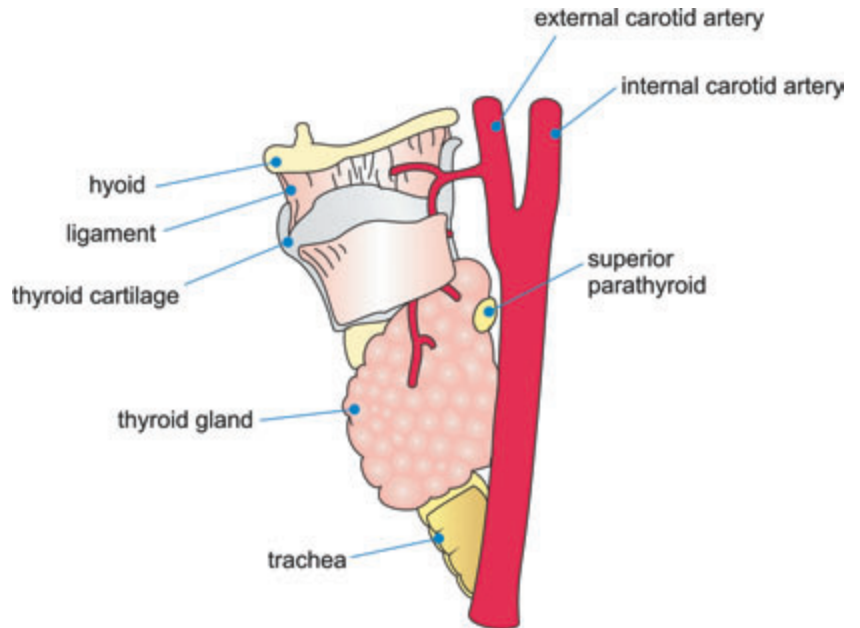
Figure 8.52 Sagittal view of the thyroid gland and its relationships.
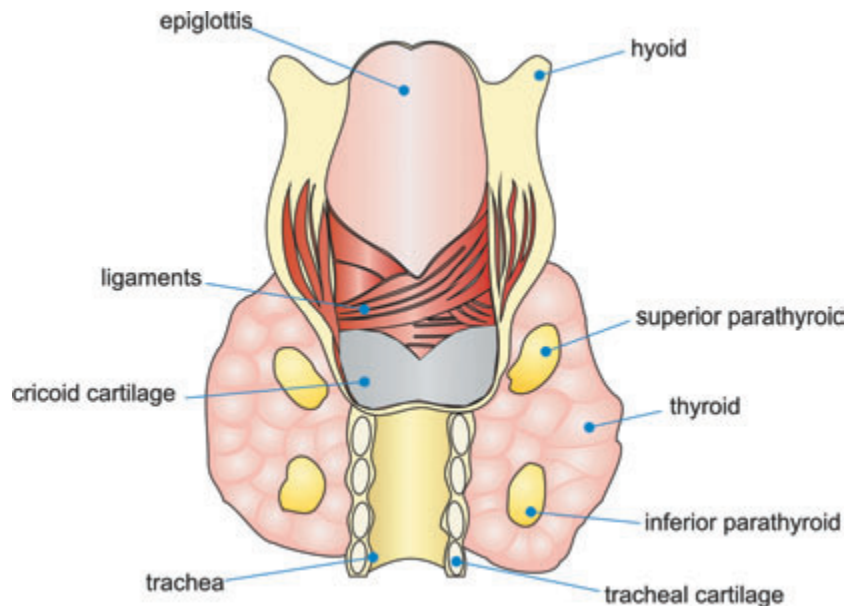
Figure 8.53 Anterior view of the thyroid gland and its relationships.

Common indications

- Retrosternal goitre.
- Evaluation of recurrent thyroid carcinoma.
- Detection and characterization of parathyroid adenoma.

Equipment

- Anterior neck coil/volume neck coil.
- Immobilization foam pads and straps.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch. The coil is placed around or anterior to the patient's neck. The patient's head is straightened as this usually straightens the neck as well. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes just inferior to the thyroid cartilage (Adam's apple). The vertical alignment light should be located midway between the posterior and anterior surfaces of the neck. A soft pad may be placed under the patient's neck to facilitate this, although many dedicated coils ensure that the neck naturally assumes the correct position. Straps and foam pads are used for immobilization.

8

Suggested protocol

Coronal SE/FSE T1

Thin slices/gap are prescribed through the thyroid relative to the vertical alignment light. The area from the mandible to the arch of the aorta is included in the image.

A 0 mm to A 20 mm

Axial/Coronal SE/FSE T1

Thin slices and gap are prescribed through the thyroid or ROI. Slices are displaced inferiorly for retrosternal goitre (Figure 8.54).

Axial/Coronal SE/FSE PD/T2

Slice prescription as for the Axial/Coronal T1.
    Chemical/spectral presaturation/STIR is sometimes required for the parathyroid glands.
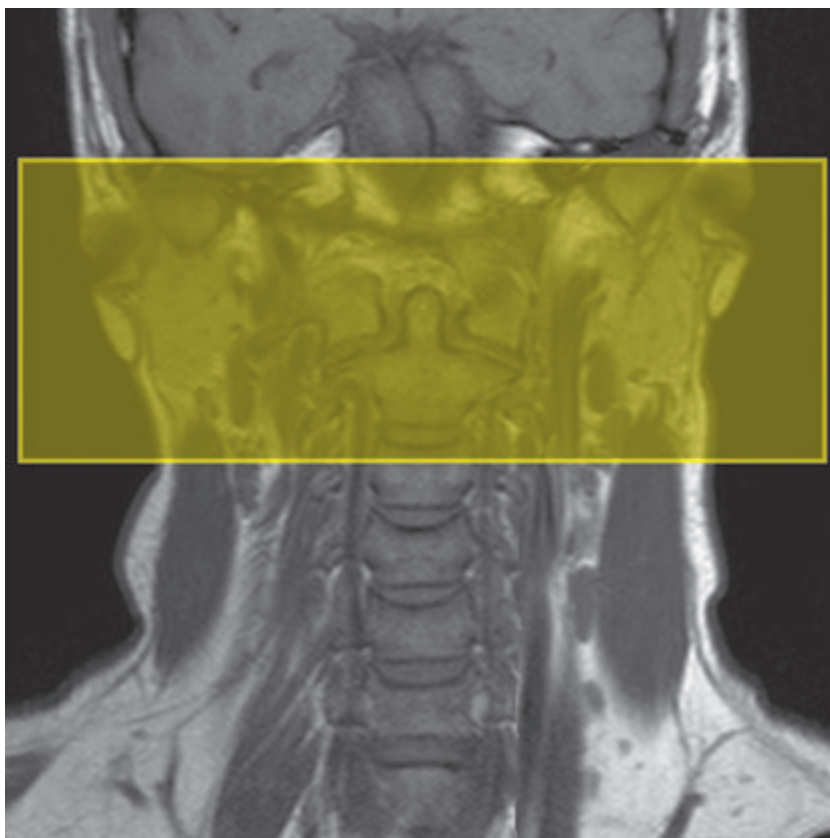
Figure 8.54   Coronal T1 weighted image showing slice prescription boundaries and orientation for axial imaging of the larynx.

8

Image optimization

Technical issues

The anterior portion of the neck is a notoriously difficult area to examine. The SNR is often poor, especially if a substandard coil is used. An anterior neck coil moulded to the face and neck is probably the best coil for this examination. However, even with these coils, multiple NEX/NSA are often necessary to maintain SNR. Spatial resolution is also important in this area, and therefore thin slices/gap and a fairly fine matrix are required to optimize resolution. The use of these matrices and multiple NEX/NSA often leads to long scan times.

A solution to these problems is the use of FSE in conjunction with a rectangular/asymmetric FOV. FSE reduces the scan time significantly and yields higher SNR, especially on the T2 weighted sequences. A rectangular/asymmetric FOV allows the acquisition of fine matrices in shorter scan times. In coronal and axial imaging, the long axis of the rectangle is placed S to I and A to P, respectively. The parathyroid gland sometimes

returns a very high signal on FSE T2 weighted sequences necessitating the use of chemical/spectral presaturation techniques.

Artefact problems

Artefact in this region arises from flow in the carotid, vertebral and jugular vessels, and from swallowing. Spatial presaturation pulses placed S and I to the FOV reduce flow artefact significantly. Bringing the spatial presaturation pulses into the FOV increases their effectiveness, but care must be taken that they do not obscure important anatomy. GMN further reduces artefact but, as it also increases signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences.

Swallowing is commonly troublesome in this area. Using multiple NEX/NSA to average out motion artefact reduces phase ghosting but leads to longer scan times. The patient should be advised to swallow as little as possible during the examination. Respiratory motion may move the anterior neck coil during the acquisition of data. If this is a problem, instruct the patient to breathe shallowly. In addition, small foam pads placed between the chest and the coil help to reduce coil movement.

Patient considerations

A careful explanation of the procedure and the importance of minimizing swallowing during the examination are important. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

This is rarely indicated but may be useful to distinguish the extent or nature of a lesion.

8

Salivary glands

Basic anatomy (Figure 8.55)
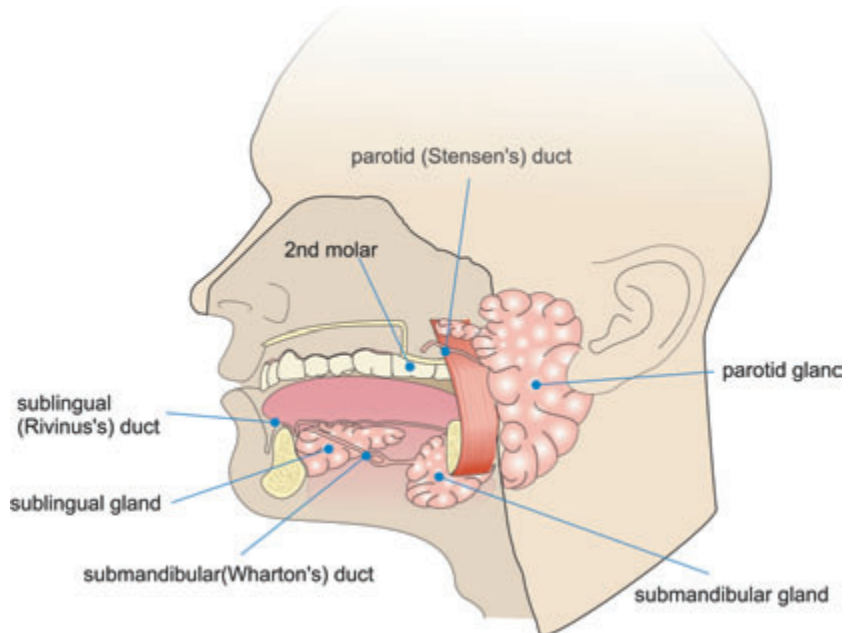
Figure 8.55   The salivary glands and their ducts.

Common indications

- Detection of salivary gland masses.
- Staging of neoplasms and nodal involvement.

Equipment

- For parotid glands: Quadrature or multi-coil array head coil. Foam pads and immobilization straps.
- For submandibular glands and cervical nodes: Anterior/volume neck coils. Foam pads and immobilization straps.
- Ear plugs.

Patient positioning

For parotid glands

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the interpupillary line is parallel

to the couch and the head is straight. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the external auditory meatus. Straps and foam pads are used to immobilize the patient.

For submandibular glands and cervical nodes

The patient lies supine on the examination couch. The coil is placed around or anterior to the patient's neck. Care should be taken to include the floor of the mouth within the coil. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the angle of the jaw. The vertical alignment light should be located midway between the posterior and anterior surfaces of the neck. A soft pad may be placed under the patient's neck to facilitate this, although many dedicated coils ensure that the neck naturally assumes the correct position.

Suggested protocol

Sagittal SE T1

Thin slices/gap are prescribed on either side of the longitudinal alignment light. The area from the base of the skull to the hyoid bone is included in the image to visualize both the parotid and submandibular glands.

L 37 mm to R 37 mm

Coronal SE/FSE T1

Mainly demonstrates the parotid glands. Thin slices/gap are prescribed from the vertebral bodies posteriorly to the superior alveolar process. The cervical lymph node chain and the skull base are included in the image.

Axial SE/FSE T1

Thin slices/gap are prescribed from the superior aspect of the external auditory meatus to the angle of the jaw for the parotid glands, or through the submandibular glands (located just below the mandible). Coverage is extended for tumour spread.

Axial SE/FSE PD/T2

Demonstrates abnormal tissue and dilated ducts in the diagnosis of salivary gland masses. Thin slices/gap are prescribed through both glands. Coverage is extended for tumour spread. Chemical/spectral presaturation/STIR is sometimes necessary in imaging of the parotid gland.

8

Additional sequences

SS-FSE/FSE T2

MR sialography may be of use in investigating ductal obstruction of the salivary system. Heavily T2 weighted images are acquired and post-processed (*see Liver and biliary system*, and *Kidneys and adrenals* and *Pancreas* later in Part 2 for the use of this technique in other areas).

Image optimization

Technical issues

The salivary glands are relatively small structures and therefore spatial resolution is important. The SNR is optimized by using the correct coil. The parotid glands are commonly examined using a quadrature or phased array head coil that yields high and uniform signal. The submandibular glands can sometimes be imaged using this coil, as long as the patient is able to move well inside it; otherwise an anterior neck coil is necessary. Thin slices and fine matrices are important to maintain the necessary resolution and, as a result, multiple NEX/NSA are commonly required to maintain SNR. The use of FSE in conjunction with a rectangular/asymmetric FOV also improves SNR and facilitates the acquisition of fine matrices in relatively short scan times. Fat suppression techniques are sometimes required in FSE T2 weighted sequences as the fatty components of the parotid gland return a signal similar to pathology. The ductal salivary system may be effectively visualized using heavily T2 weighted FSE images (MR sialography). The use of long TEs (250 ms), TRs (10 s) and ETLs (16–20) produces images where the only signal returned is from fluid within the duct. As the ducts are small, good resolution is also required therefore 3D acquisitions may be superior to 2D.

Artefact problems

The main source of artefact in this area is from the carotid, jugular and vertebral vessels. Spatial presaturation pulses placed S and I to the FOV diminish this. GMN further minimizes flow artefact but, as it also increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. Phase ghosting occurs along the R to L axis in axial and coronal imaging, and interferes with the laterally situated parotid glands. Swapping the phase axis so that it lies S to I reduces this problem, but oversampling is often necessary. Swallowing is often troublesome especially when examining the submandibular glands. Spatial presaturation bands placed carefully over the throat help to reduce this but may obscure the glands themselves. Instructing the patient to swallow as little as possible during the acquisition of data is advisable.

8

Patient considerations

Some patients with oral pathology produce copious saliva and have difficulty swallowing. This often leads to choking or major swallowing artefact. Try to calm and reassure the patient as much as possible before the examination. Give the patient plenty of tissues and, in extreme circumstances, consider examining the patient prone. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely given but may be helpful to distinguish pathology from normal anatomy.

8

Temporomandibular joints

Basic anatomy (Figure 8.56)
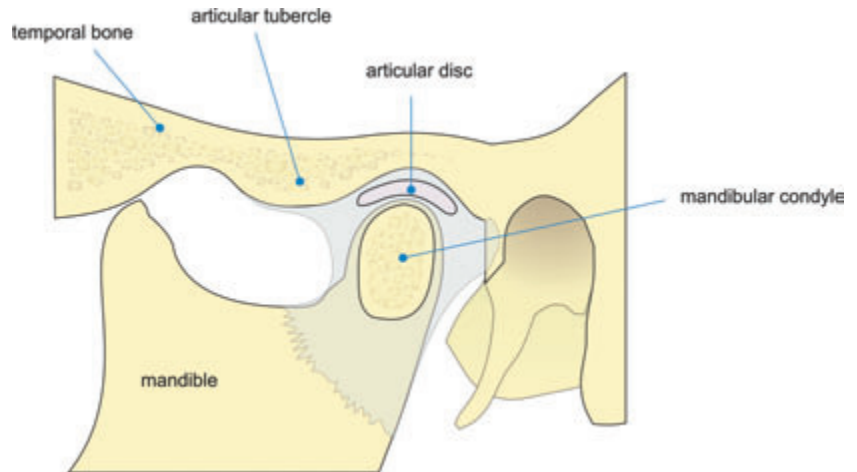
Figure 8.56 Sagittal/oblique view of the components of the temporomandibular joint (TMJ).

Common indications

- Suspected internal meniscal derangement.

Equipment

- Dual three inch coils/multi-coil array temporomandibular joint (TMJ) coils.
- Mouth opening device.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with the coils secured over the TMJs. These can be located by placing fingers just anterior to the external auditory meati and asking the patient to open and close their mouth. The coils are placed as close as possible, but not touching the face, with the receiving side of the coils towards the patient. Both joints are imaged together so the patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the TMJs (which is the centre of the coils). Straps and foam pads are used for immobilization.

Before the examination, the function of the mouth opener is explained to the patient. The patient practises the opening of the device before the

examination to minimize the risk of movement after the examination has begun. The first closed mouth acquisition should be made without the device in the patient's mouth. In some cases of anterior dislocation, it is possible that the meniscus will recapture immediately upon insertion of the device into the patient's mouth. When ready, the patient is asked to open their mouth with the opening device until they feel their jaws about to click. The operator can advise the patient when to do this over the system intercom. If a mouth opening device is not available, various size syringe barrels can be used to hold a patient's mouth open at various stages as desired.

Suggested protocol

Axial SE/FSE T1 (mouth closed) (Figure 8.57)

Include the whole head so that the correct position of both coils is ascertained. Medium slices/gap are prescribed on either side of the horizontal alignment light. Both TMJs are included in the image.

I 15 mm to S 15 mm
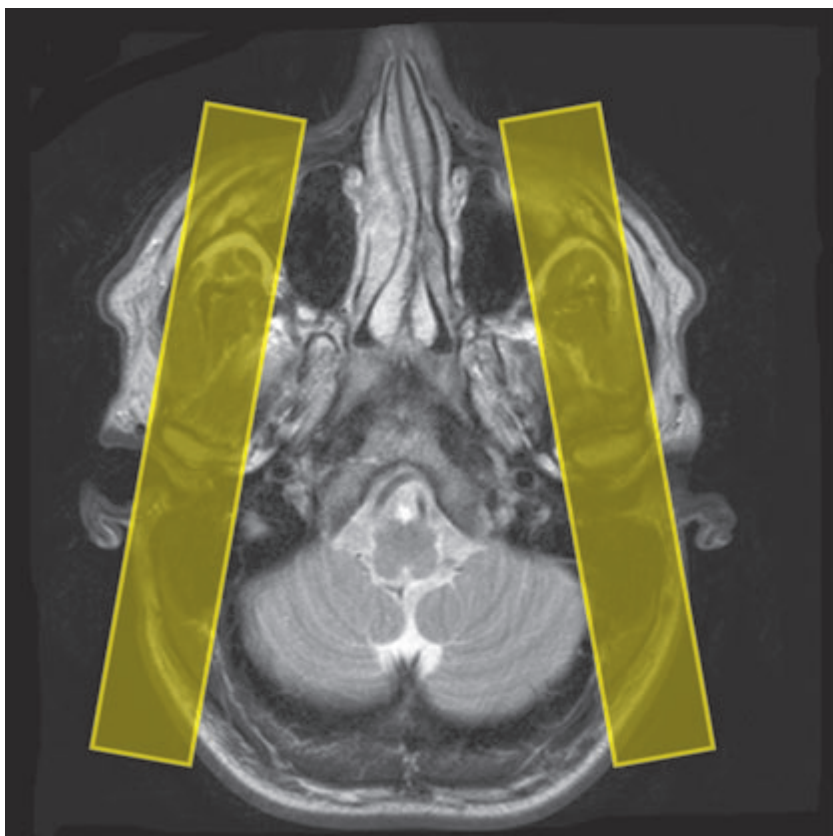
Figure 8.57 Axial SE T1 weighted localizer through the temporomandibular joints (TMJs) showing correct placement of sagittal/oblique slices perpendicular to the mandibular condyles.

Sagittal/oblique T1 (mouth closed)

Thin slices/gap or interleaved are prescribed through each joint. Slices are angled so that they are perpendicular to the mandibular condyles (do not over-oblique these) (Figure 8.57).

Sagittal/oblique T1 (mouth open)

Slice prescription as for mouth closed.

Additional sequences

Coronal/oblique T1

As for the Sagittal/obliques, **except** slices are either prescribed perpendicular to the sagittal/obliques, or in the orthogonal coronal plane through both joints. Mouth open or closed.

Sagittal/oblique FSE/SS-FSE/EPI during mouth opening and closing

For dynamic imaging of the TMJ.

3D incoherent (spoiled) GRE/FSE T1

For thinner slices than 2D acquisitions and reformatting in other planes.

8

Image optimization

Technical issues

The SNR depends largely on the quality of the coils. Spatial resolution is important as the structures within the joint are small and therefore a small FOV, thin slices, interleaving, and relatively fine matrices are necessary. As the FOV is small, multiple NEX/NSA are often required to maintain adequate SNR and therefore scan times may be of several minutes duration. A common mistake is to over-oblique the sagittal/oblique slices. Ensure that they are perpendicular to the mandibular condyles. Dynamic imaging of the TMJs may be useful in assessing meniscal derangement. However, unless the sequence used is very rapid, temporal resolution may be insufficient and a pseudo-dynamic set of images are produced, i.e. where a single slice is acquired at each static position of mouth opening and the images are viewed sequentially in a cine mode. This type of acquisition may not show true movement of the disc during mouth opening. In order to achieve this, the temporal resolution must be high, and real-time imaging using sequences such as EPI is required (see *Dynamic imaging* under *Pulse sequences* in Part 1).

Artefact problems

Pulsation from the carotid vessels often interferes with the image. Spatial presaturation pulses placed S and I to the FOV are effective, but ghosting is sometimes seen. GMN also minimizes flow artefact but, as it increases signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. As the images are obliqued there may be no operator control over the phase and frequency axes. If, however, the system allows for axes control, placing phase S to I is probably the best option as this largely removes the artefact from the joint. As a small FOV is used, oversampling is usually necessary.

Patient considerations

Patient cooperation is important during this examination. The patient should practise using the mouth opening device before the examination. The technologist must explain that the mouth is opened until the patient feels that the jaw is about to click, and then relaxed so that the upper and lower jaws rest against the opener. As scan times are often lengthy, swallowing whilst the mouth is open can cause motion artefact. Obviously the patient must swallow if absolutely necessary, but it should be discouraged if possible. Another common problem is that the patient often moves from the localizer position when he or she opens their mouth. It is wise to obtain a second localizer with the mouth open to ensure adequate coverage of the second set of sagittal/obliques.

Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not commonly used in this area. However, arthrography of the joints may prove useful in the future. The joint is injected with a small amount of gadolinium followed by sagittal/oblique T1 weighted imaging.

8

Vascular imaging

Basic anatomy (Figure 8.58)

anterior communicating artery

middle cerebral artery

anterior cerebral artery

posterior communicating artery

posterior cerebral artery

internal carotid

basilar artery

vertebral artery
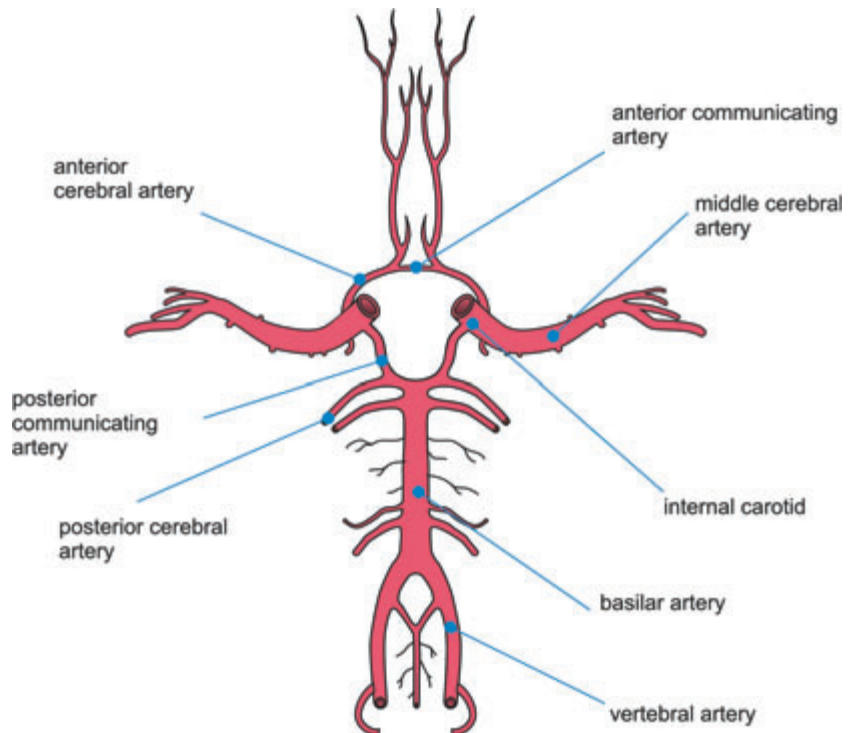
Figure 8.58   The Circle of Willis providing vascular supply to the brain.

8

Common indications

- Evaluation of the carotid arteries especially at the bifurcation.
- Intracranial vascular assessment of aneurysms and infarcts.
- Arterio-venous malformation (AVM).
- Intracranial vessel occlusion including sagittal sinus thrombosis.

Equipment

- Quadrature or phased array head coil (brain imaging).
- Anterior neck coil (neck imaging).
- Immobilization foam pads and straps.
- Ear plugs.

Patient positioning

Brain imaging

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the interpupillary line is parallel to the couch and the head is straight. The longitudinal alignment light lies in the midline and the horizontal alignment light passes through the nasion. Straps and foam pads are used to immobilize the patient as much as possible.

Neck imaging

The patient lies supine on the examination couch and an anterior neck coil is secured so that the base of the skull to the arch of the aorta are included within the volume of the coil. The longitudinal alignment light lies in the midline and the horizontal alignment light passes through the angle of the jaw.

Suggested protocol

Vascular imaging in the brain (Figures 8.59 and 8.60)

A sagittal SE T1 series can be performed as a localizer. This is then followed by either 3D TOF or PC images. 3D acquisitions allow for increased SNR and very thin contiguous slices, so improving the spatial resolution. Depending on the coverage required, 28 to 124 thin slice locations may be selected. In PC-MRA all three axes are usually flow encoded. Due to the increased likelihood of intra-slab flow saturation with 3D TOF-MRA, PC-MRA is usually the sequence of choice for volume imaging in the head. However, intra-slab flow saturation in 3D TOF-MRA is improved by the implementation of ramped flip angles. 2D TOF-MRA is reserved for visualizing intracranial venous flow or small peripheral vessels. If MRA software is not available, cine or ultrafast coherent GRE T2* sequences in conjunction with GMN are beneficial, especially in the visualization of sagittal sinus thrombosis and post-embolization of giant aneurysms. When used in conjunction with SE sequences, spatial presaturation pulses produce black blood. If signal persists in a vessel it may indicate either slow flow or occlusion. When used in conjunction with GRE sequences, GMN produces bright blood. If a signal void is seen within the vessel, it may indicate either slow flow or occlusion.

Vascular imaging in the neck (Figure 8.61)

A coronal coherent GRE sequence can be performed as a localizer. Axial 2D TOF-MRA using thin slices prescribed through the carotid and bifurcation are required, followed by 3D TOF-MRA for improved resolution

Figure 8.59 Contrast enhanced-multiphase images of the brain.

8
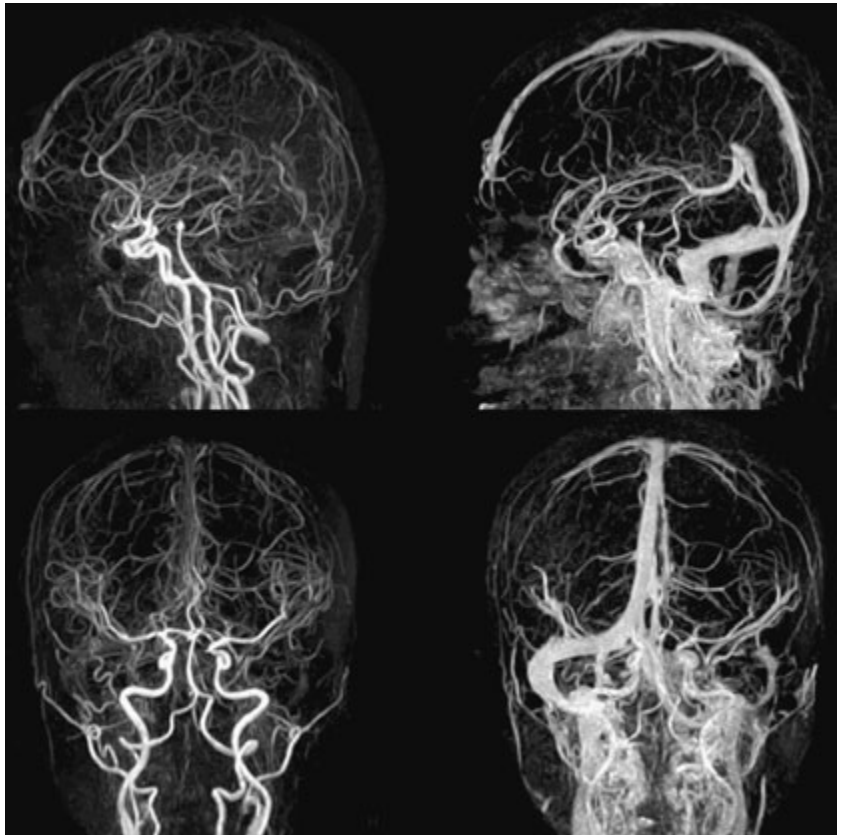
Figure 8.60 Phase contrast venogram of the brain.
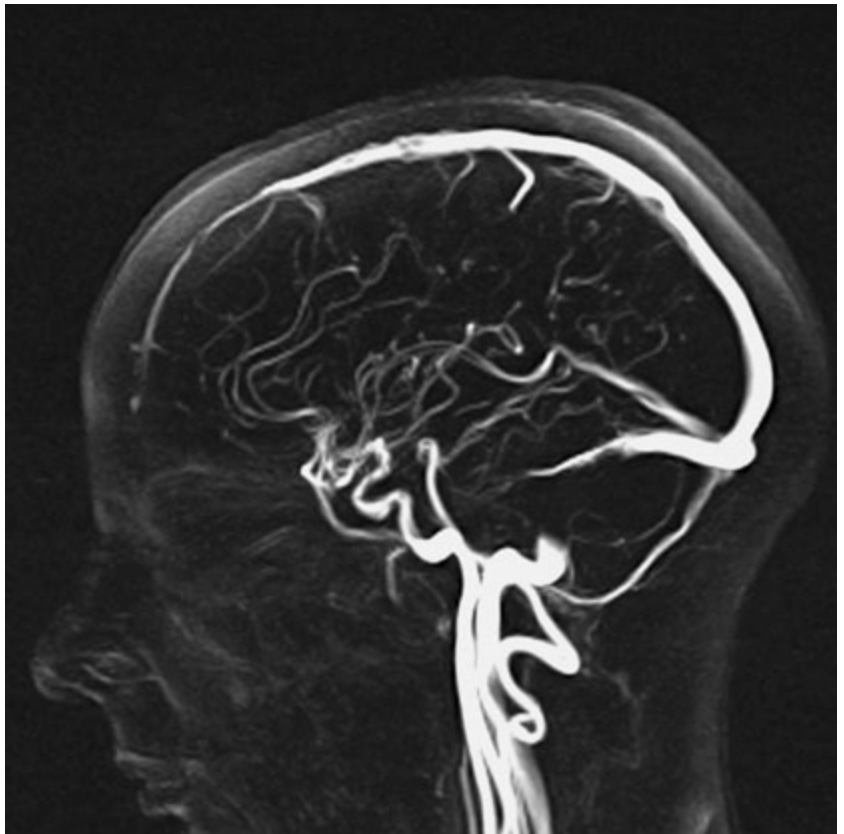
Figure 8.61   Coronal contrast enhanced MRA of the neck vessels.
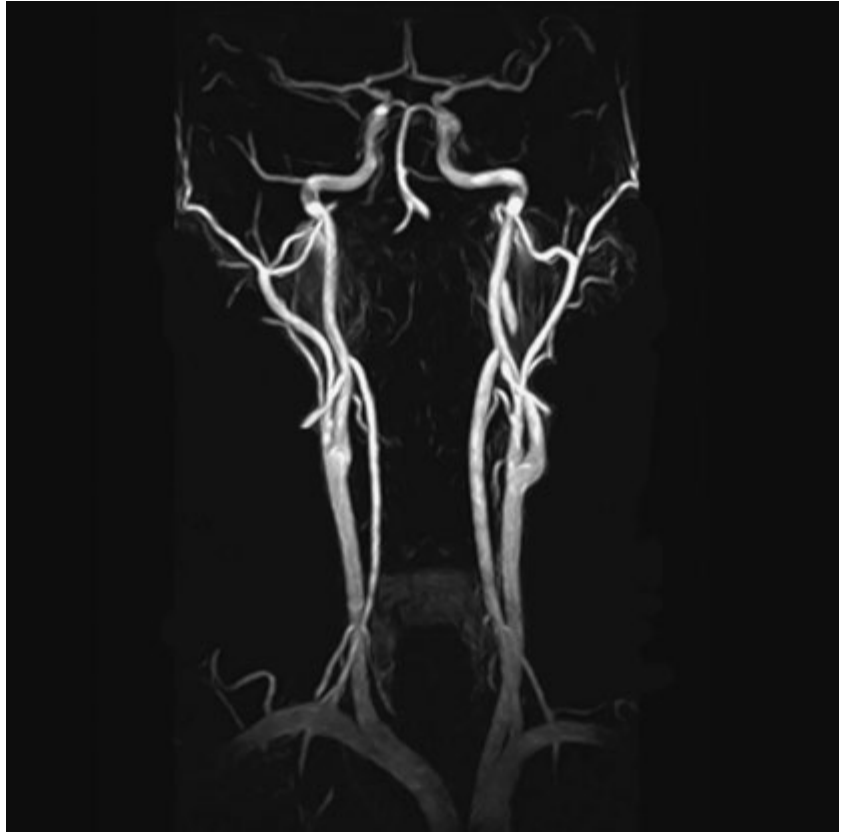
of the bifurcation. Spatial presaturation pulses should be placed S to the FOV to saturate venous flow entering the slice stack from above. If MRA software is not available, the carotid vessels can sometimes be adequately visualized using conventional 3D coherent GRE T2* sequences in conjunction with GMN, although the resolution is not as good as in conventional MRA imaging. In addition, when used in conjunction with SE sequences, spatial presaturation pulses produce black blood. If signal persists in a vessel it may indicate either slow flow or occlusion. When used in conjunction with GRE sequences, GMN produces bright blood. If a signal void is seen within the vessel, it may indicate either slow flow or occlusion.

Image optimization

Technical issues

The quality of MRA images depends on a variety of factors. First, the type of sequence used is important. Most examinations require both TOF

and 3D PC sequences to visualize all the cerebral vasculature adequately. TOF-MRA is beneficial when imaging flow that moves perpendicular to the slice plane. Therefore it should be reserved for the Circle of Willis and peripheral intracranial vessels. 3D TOF-MRA can result in a loss of signal from nuclei becoming saturated within the slice stack, and is mainly valuable on faster arterial flow unless ramped flip angles are available.

Spatial presaturation pulses are carefully placed so as only to saturate unwanted flow. The use of GMN and MT in TOF-MRA sequences improves image contrast by increasing the signal within vessels (GMN), and suppressing background signal (MT) (see *Pulse sequences* in Part 1). Scan times are lengthy, especially in PC-MRA where the scan time is dependent (among other things) on the number of flow encoding axes implemented. Image quality also depends on the accurate setting of flow encoding axis and VENCs. Fast 2D images acquired before the 3D acquisition often help to determine the direction and speed of flow.

Artefact problems

In TOF-MRA, signal from the fatty components of the orbit and the scalp are commonly not saturated adequately and therefore interfere with the image. This is due to the short recovery times of these tissues. Chemical/spectral presaturation often successfully reduces this unwanted signal, but on some systems may also saturate the vessels. Alternatively, using a TE when the fat and water signals are out of phase with each other and applying MT usually adequately suppresses background signal. Motion artefact is sometimes troublesome especially on 3D PC-MRA images as their acquisition times are very long, and any motion of flowing nuclei within the vessels produces signal.

Patient considerations

Some of these patients may be incapacitated by their illness especially if this involves tumours, AVM or stroke. A careful explanation of the examination and the approximate length of the study are required. In brain imaging, claustrophobia is sometimes troublesome due to the enclosing nature of the head coil. Ensure that the coil mirror is adjusted and that the patient is provided with an alarm bell.

Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Due to the inherent contrast between vessels and background tissue, these examinations do not usually require IV contrast. However, the use of contrast increases vessel conspicuity as it shortens the T1 of blood, increases vessel signal and improves image contrast in TOF-MRA sequences (Figures 8.59 and 8.61).

9

Spine

9

Table 9.1   Summary of parameters. The figures given are general and should be adjusted according to the system used (Table 2.1)

Spin echo (SE)

short TE	min to 30 ms
long TE	70 ms +
short TR	300−600 ms
long TR	2000 ms +

Fast spin echo (FSE)

short TE	min−20 ms
long TE	90 ms +
short TR	400−600 ms
long TR	4000 ms +
short ETL	2−6
long ETL	16 +

Inversion recovery (IR) T1

short TE	min−20 ms
long TR	3000 ms +
medium TI	200−600 ms
short ETL	2−6

STIR

long TE	60 ms +
long TR	3000 ms +
short TI	100−175 ms
long ETL	12−20

FLAIR

long TE	60 ms +
long TR	3000 ms +
long TI	1700−2200 ms
long ETL	12−20

Coherent GRE

long TE	15 ms +
short TR	≤ 50 ms
flip angle	20°−40°

Incoherent GRE

short TE	min−5 ms
short TR	≤ 50 ms
flip angle	20°−40°

Balanced GRE

TE	minimum
TR	minimum
flip angle	≥ 40°

SSFP

TE	minimum
TR	40−50 ms
flip angle	20°−40°

Slice thickness

2D	thin	2−4 mm
	medium	5−6 mm
	thick	8 mm
3D	thin	≤ 1 mm
	thick	≥ 3 mm

Slice numbers

Volumes	small	≤ 32
	medium	64
	large	≥ 128

Matrix (frequency × phase)

coarse	256 × 128 or 256 × 192
medium	256 × 256 or 512 × 256
fine	512 × 512
very fine	≥ 512 × 512

FOV

small	≤ 18 cm
medium	18−30 cm
large	≥ 30 cm

PC-MRA

2D and 3D	TE		minimum
	TR		25−33 ms
	flip angle		30°
VENC venous		20−40 cm/s	
VENC arterial		60 cm/s	

NEX/NSA

short	≤ 1
medium	2−3
multiple	≥ 4

TOF-MRA

2D	TE	minimum
	TR	28−45 ms
	flip angle	40°−60°
3D	TE	minimum
	TR	25−50 ms
	flip angle	20°−30°

9

Cervical spine

Basic anatomy (Figures 9.1 and 9.2)

Figure 9.1 Sagittal view of the spine showing vertebral levels.

9

Common indications

- Cervical myelopathy.
- Cervical radiculopathy.
- Cervical cord compression or trauma.
- Assessment of extent of spinal infection or tumour.
- Diagnosis of Chiari malformation and cervical syrinx. (Total extent of syrinx must be determined. Whole spine imaging may be necessary.)
- MS plaques within the cord.
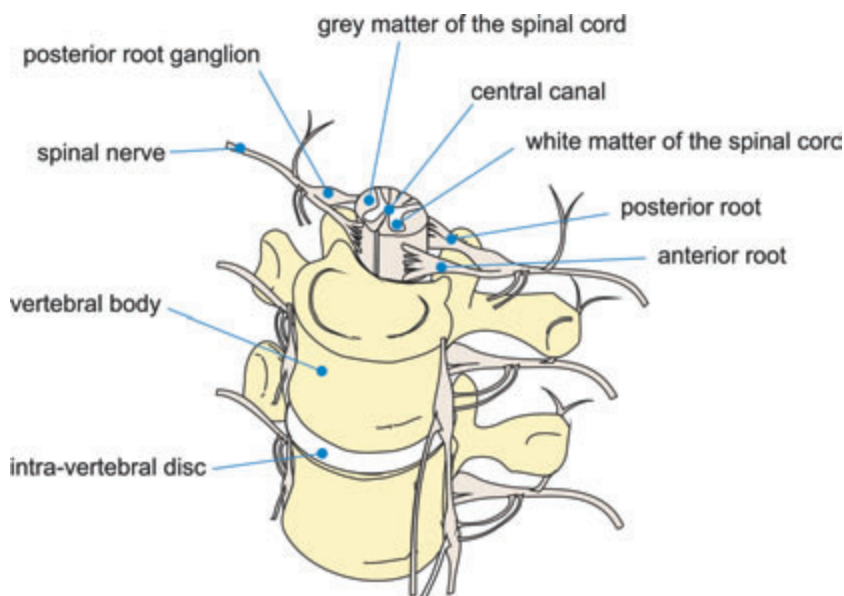
Figure 9.2   The components of the spine and spinal cord.

Equipment

- Posterior cervical neck coil/volume neck coil/multi-coil array spinal coil.
- Immobilization pads and straps.
- Pe gating leads if required.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with the neck coil placed under or around the cervical region. Coils are often moulded to fit the back of the head and neck so that the patient is automatically centred to the coil. If a flat coil is used, placing supporting pads under the shoulders flattens the curve of the cervical spine so that it is in closer proximity to the coil. The coil should extend from the base of the skull to the sternoclavicular joints in order to include the whole of the cervical spine.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the hyoid bone (this can usually be felt above the thyroid cartilage/Adam's apple). The patient's head is immobilized with foam pads and retention straps. Pe gating leads are attached if required.

9

Suggested protocol

Sagittal/coronal SE/FSE T1 or coherent GRE T2*

Acts as a localizer if three-plane localization is unavailable. The coronal or sagittal planes may be used.

Coronal localizer: Medium slices/gap are prescribed relative to the vertical alignment light, from the posterior aspect of the spinous processes to the anterior border of the vertebral bodies. The area from the base of the skull to the second thoracic vertebra is included in the image.

P 20 mm to A 30 mm

Sagittal localizer: Medium slice thickness/gap are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of the vertebral bodies. The area from the base of the skull to the second thoracic vertebra is included in the image.

L 7 mm to R 7 mm

Sagittal SE/FSE T1 (Figure 9.3)

Thin slices/gap are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of the vertebral bodies (unless the paravertebral areas are required). The area from the base of the skull to the second thoracic vertebra is included in the image.

L 22 mm to R 22 mm

Sagittal SE/FSE T2 or coherent GRE T2* (Figure 9.4)

Slice prescription as for Sagittal T1.

Axial/oblique SE/FSE T1/T2 or coherent GRE T2* (Figure 9.7)

Thin slices/gap are angled so that they are parallel to the disc space or perpendicular to the lesion under examination (Figures 9.5 and 9.6). For disc disease, three or four slices per level usually suffice. For larger lesions such as tumour or syrinx, thicker slices covering the lesion and a small area above and below may be necessary.

Additional sequences

Sagittal/axial oblique SE/FSE T1

Slice prescription as for Axial/oblique T2* with contrast enhancement for tumours.

Sagittal SE/FSE T2 or STIR

Slice prescription as for Sagittal T2*. An alternative to coherent GRE T2*.

9

Figure 9.3 Sagittal SE T1 weighted midline image through the cervical spine.
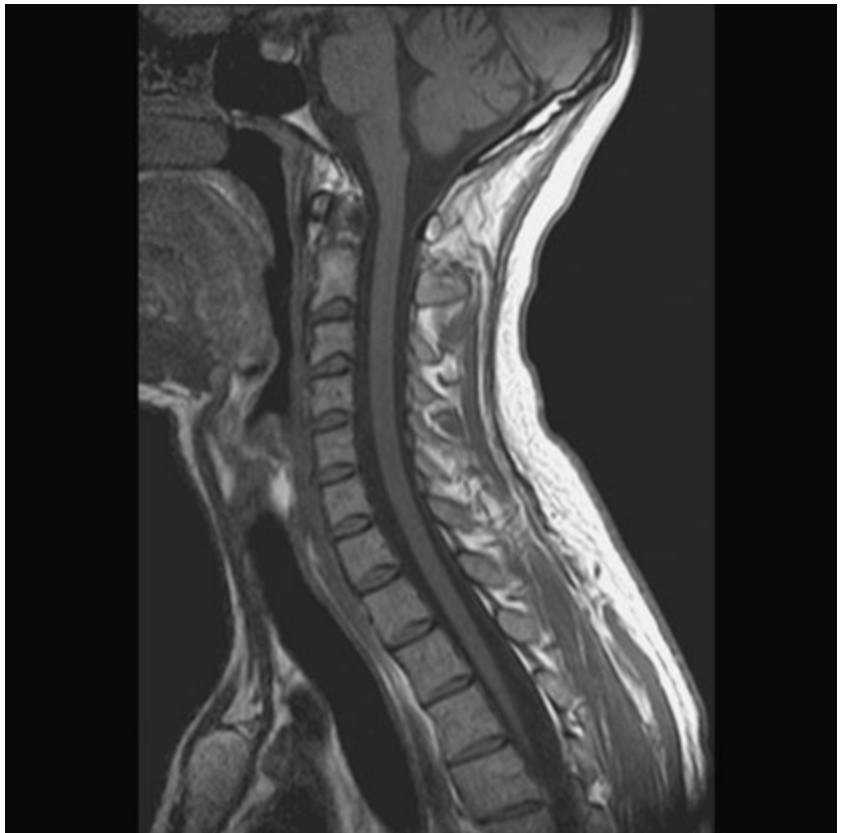
Figure 9.4 Sagittal FSE T2 weighted midline image through the cervical cord.
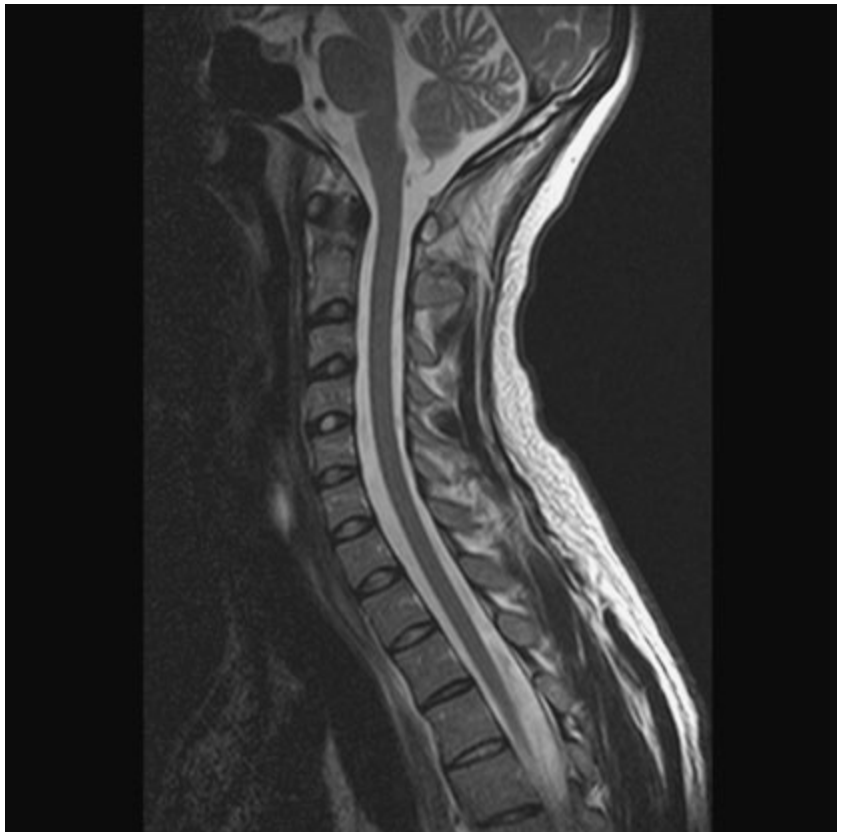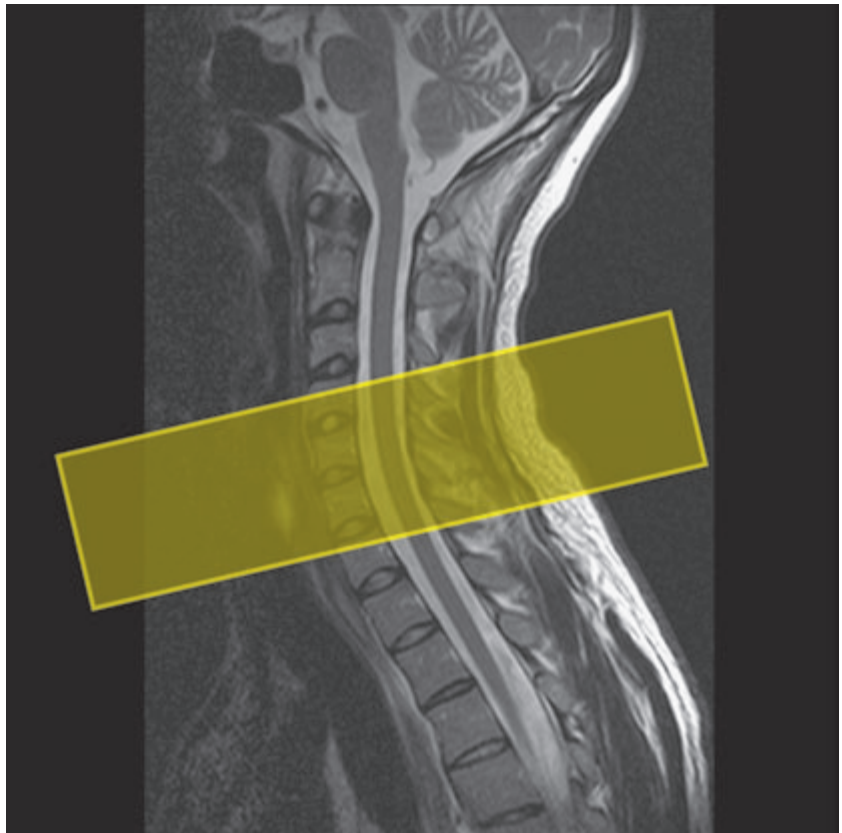
Figure 9.5 Sagittal FSE T2 weighted image showing slice prescription boundaries and orientation for axial imaging of the cervical cord.

9
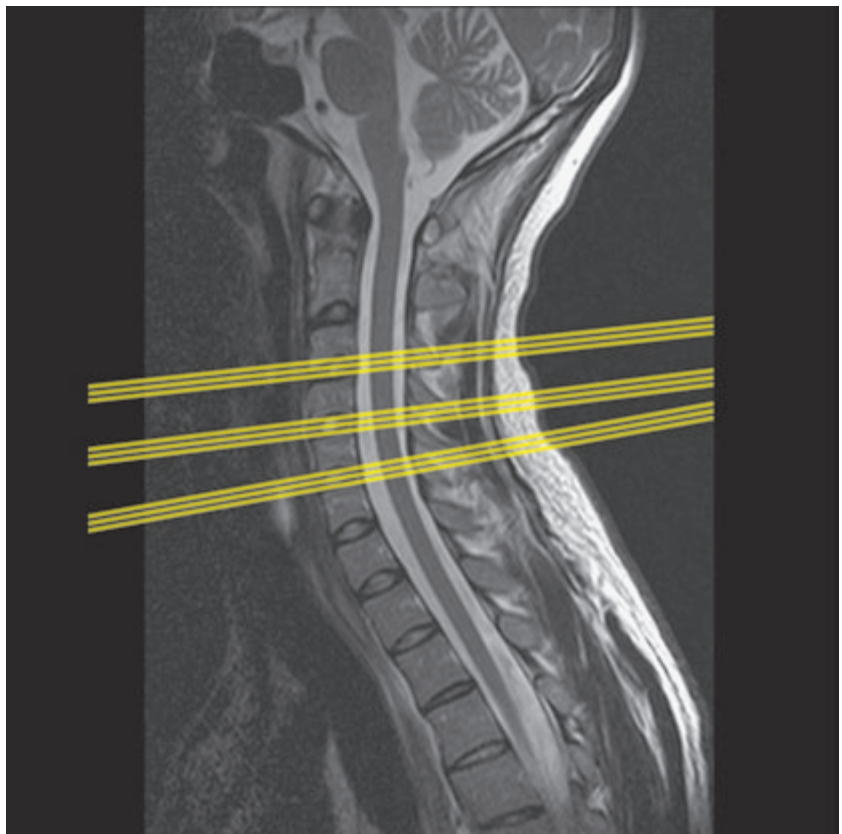
Figure 9.6 Sagittal coherent GRE T2* weighted image of the cervical spine showing axial/oblique slice positions parallel to each disc space.
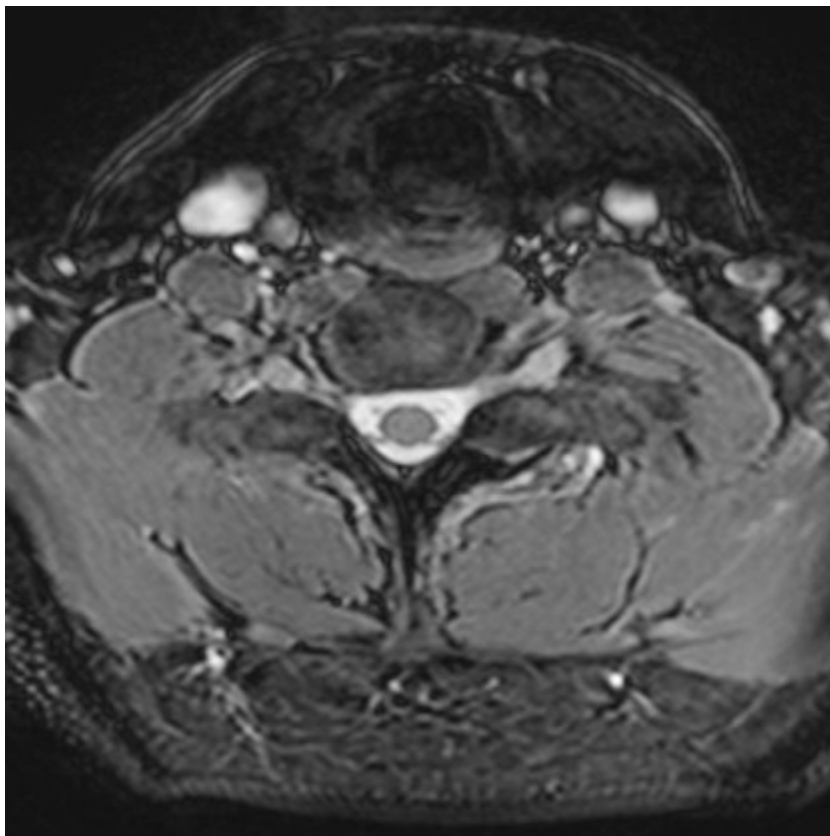
Figure 9.7 Axial/oblique coherent GRE T2* weighted image through the cervical cord.

3D coherent/incoherent (spoiled) GRE T2*/T1

Thin slices and a few or medium number of slice locations are prescribed through the ROI. If PD or T2* weighting is desired, then a coherent or steady-state sequence is utilized. If T1 weighting is required an incoherent or spoiled sequence is necessary. These sequences may be acquired in any plane but, if reformatting is required, isotropic datasets must be acquired.

Sagittal SE/FSE T1 or fast incoherent (spoiled) GRE T1/PD

Slice prescription as for Sagittal T1, T2 and T2*, **except** neck in flexion and extension to correlate the potential relevance of spondylotic changes to signs and symptoms.

3D balanced gradient echo (BGRE) (Figure 9.8)

The contrast characteristics of a BGRE sequence provide for high signal from CSF (high T2 / T1 ratio) and thus produces images with high contrast between CSF and nerve roots. It is important to remember that
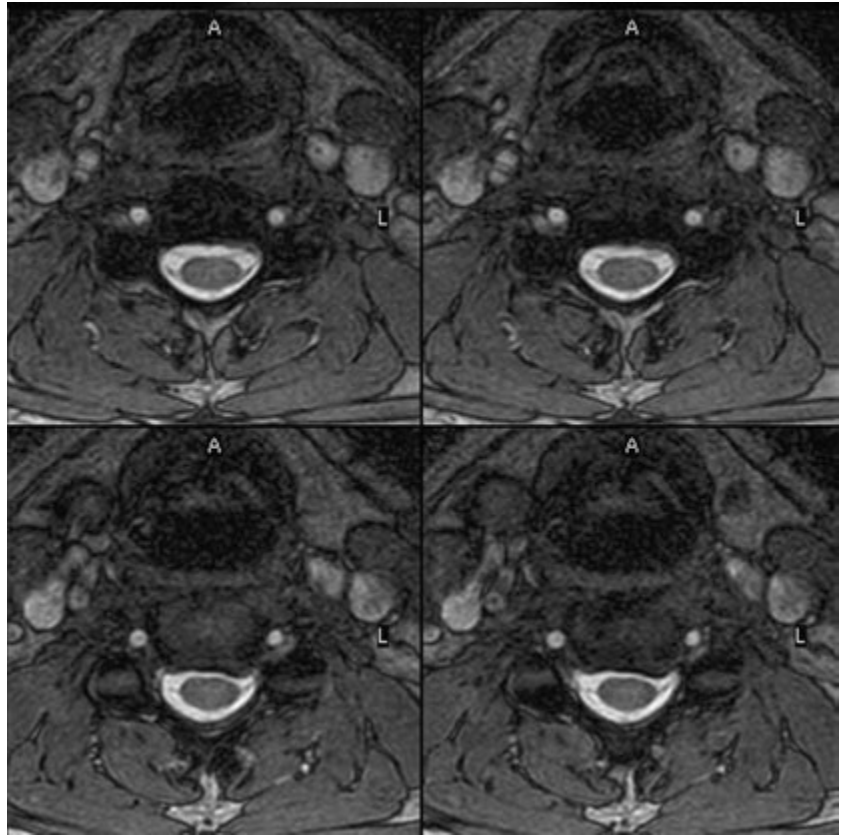
Figure 9.8 Axial balanced GRE through the cervical spine.

9

because these images are not true T2 weighted, subtle cord lesions such as MS plaques may not be seen. As such they are typically utilized when imaging a patient for radiculopathy (disk disease) rather then myelopathy (cord lesions).

Image optimization

Technical issues

The SNR in this region is mainly dependent on the quality of the coil. Posterior neck coils give adequate signal for the cervical spine and cord, but signal usually falls off at the anterior part of the neck, so they are not recommended for imaging structures such as the thyroid or larynx. In addition, flare from the posterior skin surface can be troublesome in sagittal T1 imaging, where the large fat pad situated at the back of the neck returns a high signal. Volume coils produce even distribution of signal, but the SNR in the cord is sometimes reduced compared with a posterior neck coil. Multi-coil array combinations commonly produce

optimum SNR, and may be used with a large FOV to include the thoracic spine. This strategy is important when pathology extends from the cervical to the thoracic areas of the cord, e.g. syrinx.

Spatial resolution is also important, especially in axial/oblique imaging, as the nerve roots in the cervical region are notoriously difficult to visualize. Thin slices with a small gap and relatively fine matrices are employed to maintain spatial resolution. Ideally 3D imaging is used as this allow very thin slices with no gap and the volume may be viewed in any plane (see *Volume imaging* in *Parameters and trade-offs* in Part 1). Multiple NEX/NSA are also advisable if the inherent SNR is poor. Therefore, unless FSE is utilized, scan times are often of several minutes duration.

Fortunately, a rectangular/asymmetric FOV is used very effectively in sagittal imaging as the cervical spine fits into a rectangle with its longitudinal axis running S to I. This facilitates the acquisition of fine matrices in short scan times. With a reduced FOV in the phase direction, aliasing may be a problem. In sagittal imaging, this artefact originates from the chin and the back of the head wrapping into the FOV. Increasing the size of the overall FOV or utilizing oversampling (if available) may eliminate or reduce this artefact. In addition, spatial presaturation pulses brought into the FOV to nullify signal coming from these structures are effective (see *Flow phenomena and artefacts* in Part 1).

The multiple 180° RF pulses used in FSE sequences cause lengthening of the T2 decay time of fat so that the signal intensity of fat on T2 weighted FSE images is higher than in CSE. This sometimes makes the detection of marrow abnormalities difficult. Therefore, when imaging the vertebral bodies for metastatic disease, a STIR sequence should be utilized (see *Pulse sequences* in Part 1).

Artefact problems

The cervical area is often plagued with artefact. Not only does aliasing from structures outside the FOV obscure the image, but the periodic, pulsatile, motion of CSF within the spinal canal produces phase ghosting. The speed of flow is usually quite rapid in the cervical region, and therefore conventional flow-reducing measures, such as spatial presaturation and GMN, are less effective than in the lumbar region where CSF flow is slower. On T1 weighted images, spatial presaturation pulses placed S and I to the FOV are usually sufficient. However, on T2 weighted sequences flow artefact is commonly troublesome. In addition, selecting an S–I phase direction along with oversampling can also reduce CSF flow artefact in sagittal imaging.

As FSE sometimes demonstrates more flow artefact than CSE, it is usually not utilized in the cervical spine. This is especially true on T2 weighted images where flow artefact can totally degrade the image. However, in cases where there is severe pathology such as a disc protrusion, FSE often produces images that demonstrate acceptable levels of artefact. This may be because the protruding disc locally slows down the CSF flow. In practice, it is probably worth trying FSE on the T2 images,

9

and only if the artefact is intolerable, repeat the scan using coherent GRE. However, FSE is not commonly recommended in axial/oblique imaging because of flow-related problems. When using coherent GRE T2* sequences, GMN should be implemented as this not only increases the signal from CSF, but also reduces artefact from CSF flowing down the canal within the slice. In addition the use of balanced GRE reduces flow artefact due to the implementation of balancing gradients (see *Pulse sequences* in Part 1). This rapid sequence also works well in 3D imaging as a large volume may be acquired in a short scan time. However the conspicuity of nerve roots in the exit foramina may reduce when using a GRE sequence due to the magnetic susceptibility effects. Pe gating minimizes artefact even further but, as the scan time is dependent on the patient's heart rate, it is sometimes rather time-consuming. The implementation of Pe gating is therefore best reserved for cases of severe flow artefact that cannot be reduced to tolerable levels by other measures.

Multiple NEX/NSA reduce artefact from signal averaging, but result in an increase in the scan time. Nevertheless their implementation is often necessary, especially where the SNR is poor, and flow artefact severe. Swallowing during data acquisition is a common source of artefact. Spatial presaturation pulses placed over the throat largely eliminate this, but care must be taken not to nullify signal from important anatomy. Another problem in the cervical region is truncation artefact (or Gibbs artefact) that produces a thin line of low signal in the cord and mimics a syrinx. Truncation artefact is reduced by selecting a higher phase matrix (see *Flow phenomena and artefacts* in Part 1).

Patient considerations

Some patients have difficulty placing their neck over the posterior neck coil, especially in cases of fixed deformity. It is important that the neck is as close to the coil as possible to achieve maximum SNR. Placing pads under the patient's shoulders flattens the spine, and therefore positions the back of the neck nearer to the coil. Patients with cervical cord trauma, cord compression, or tumours are often severely disabled. The magnetic safety of any stabilization devices should be established before the examination. Great care must be taken when transferring these patients on to the examination couch, and they should be moved as little as possible. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely given for disc disease. However, in cases of leptomeningeal spread of certain tumours such as medulloblastoma, contrast is invaluable. Other cord lesions such as ependymomas and pinealoblastomas also enhance well with contrast, as do infectious processes and active MS plaques. Bony tumours, especially those that return a low signal on T1 weighted images, enhance with contrast but this often

increases their signal intensity so that they are isointense with the surrounding vertebra. Under these circumstances, chemical/spectral presaturation or the Dixon technique should be implemented to reduce the signal from fatty marrow in the vertebral bodies. Inversion recovery sequences that suppress fat (STIR) should not be used in conjunction with contrast, as their inverting pulses may nullify the signal from the tumour that, as a result of contrast enhancement, now has a similar T1 recovery time to fat.

9

Thoracic spine

Common indications

- Thoracic disc disease.
- Thoracic cord compression.
- Visualization of a MS plaque in the thoracic cord.
- Thoracic cord tumour.
- To visualize the inferior extent of cervical syrinx.

Equipment

- Posterior spinal coil/multi-coil array spinal coil.
- Pe gating leads if required.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with the spinal coil extending from the top of the shoulders to the lower costal margin to ensure total coverage of the thoracic spine and conus. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the centre of the coil, which corresponds approximately to the level of the fourth thoracic vertebra. Pe gating leads are attached if required.

Suggested protocol

Sagittal/coronal SE/FSE T1 or coherent GRE T2*

Acts as a localizer if three-plane localization is unavailable. The coronal or sagittal planes may be used.

Coronal localizer: Medium slices/gap are prescribed relative to the vertical alignment light, from the posterior aspect of the spinous processes to the anterior border of the vertebral bodies. The area from the seventh cervical vertebra to the conus is included in the image.

P 40 mm to A 30 mm

Sagittal localizer: Medium slices/gap are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of the vertebral bodies. The area from the seventh cervical vertebra to the conus is included in the image.

L 7 mm to R 7 mm

9

Figure 9.9 Sagittal FSE T1 weighted midline slice through the thoracic spine.

Sagittal SE/FSE T1 (Figure 9.9)

Thin slices/gap are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of the vertebral bodies (unless the paravertebral areas are required). The area from the seventh cervical vertebra to the conus is included in the image.

L 22 mm to R 22 mm

Sagittal SE/FSE T2 or coherent GRE T2* (Figure 9.10)

Slice prescription as for Sagittal T1.

Axial/oblique SE/FSE T1 or coherent gradient echo T2* (Figure 9.12)

Thin slices/gap are angled so that they are parallel to the disc space or perpendicular to the lesion under examination (Figure 9.11). For disc disease, three or four slices per level usually suffice. For larger lesions such as tumour or syrinx, thicker slices covering the lesion and a small area above and below are necessary.
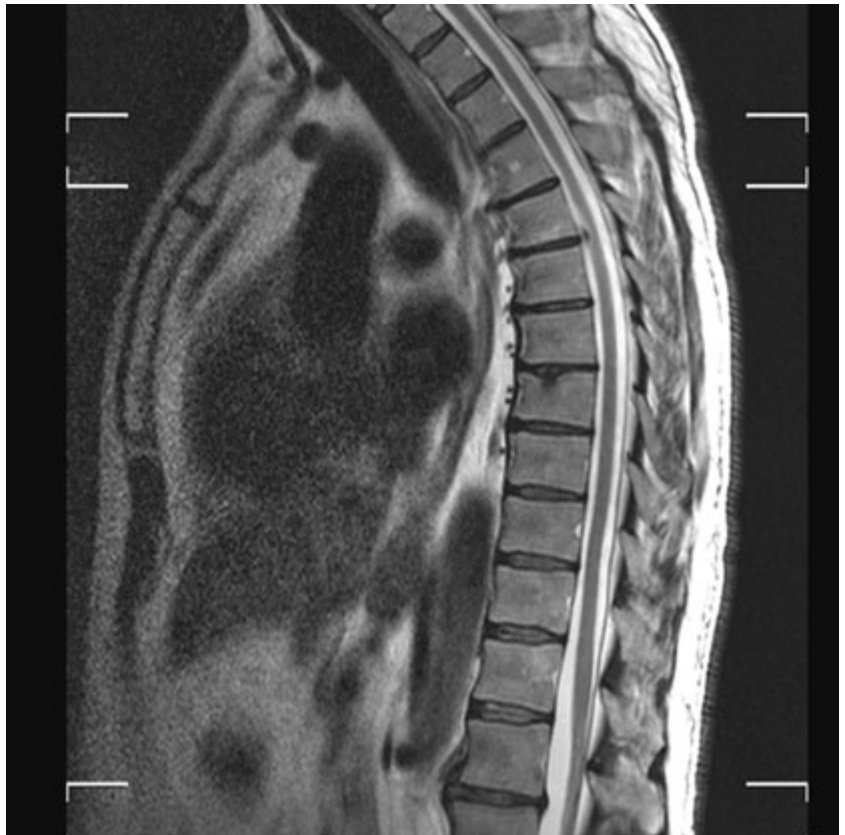
Figure 9.10 Sagittal FSE T2 weighted midline slice through the thoracic cord.
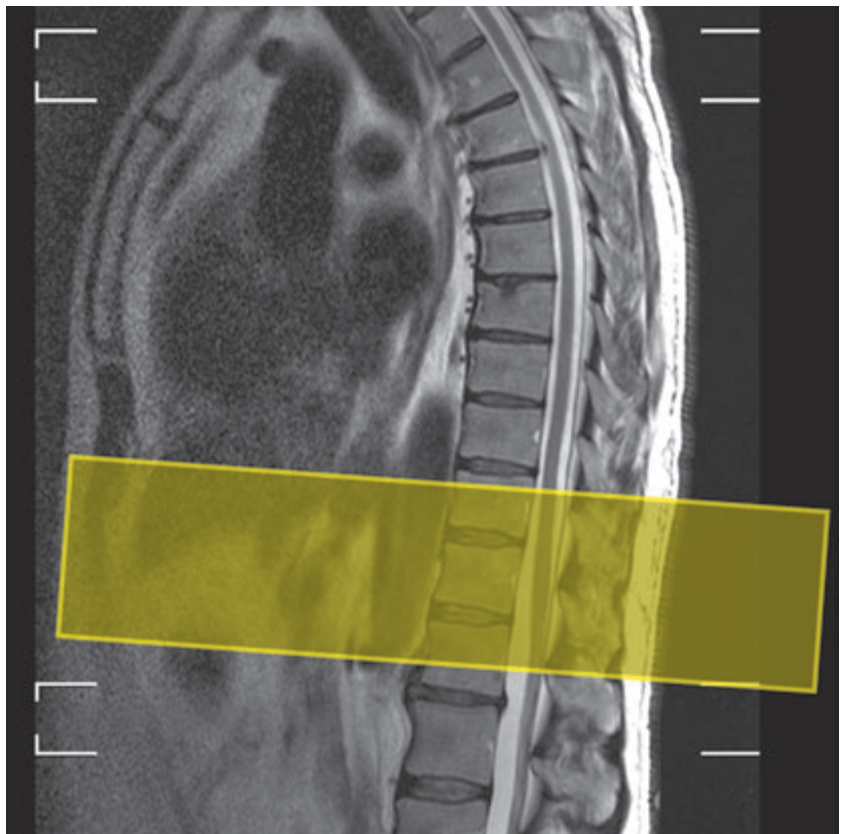
Figure 9.11 Sagittal FSE T2 weighted midline slice through the thoracic spine showing slice prescription boundaries and orientation for axial imaging of the conus.
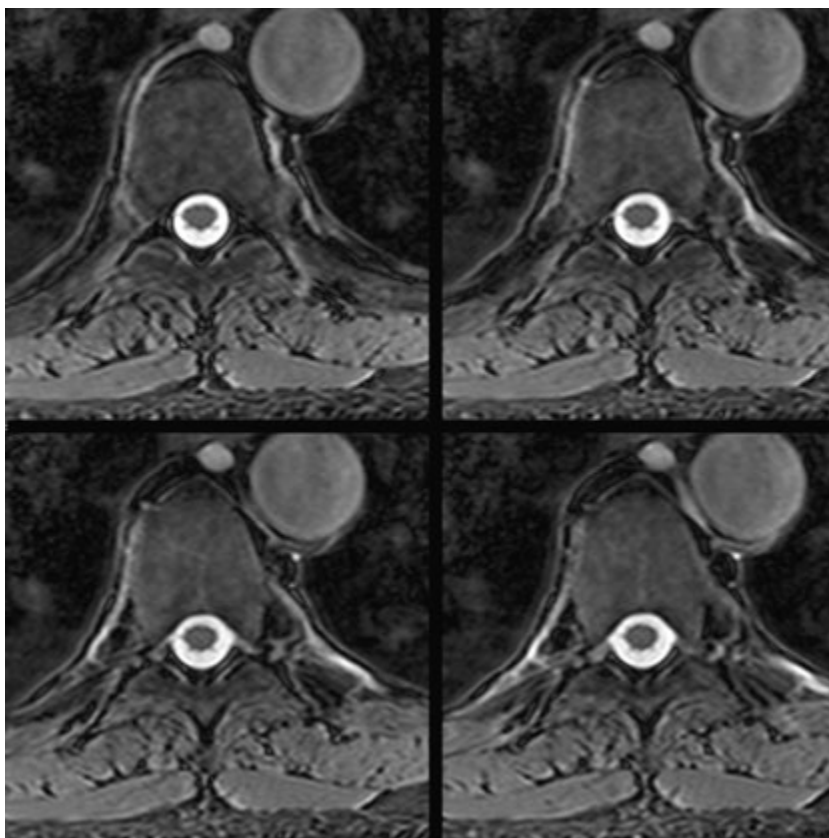
Figure 9.12 Axial/oblique FSE T2 weighted images through the thoracic cord.

9

Additional sequences

Sagittal/axial/oblique SE/FSE T1 +/– contrast

For evaluating the conus and other cord lesions.

Image optimization

Technical issues

The SNR in this region is mainly dependent on the quality of the coil. Flare from the posterior skin surface may be troublesome, especially in sagittal T1 imaging where the fatty tissues posterior to the thoracic spine return a high signal. In addition, there is signal fall-off from the anterior part of the chest due to its distance from the posteriorly situated coil. For this reason the posterior spinal coil is not utilized to image the thorax, unless the patient is a very small child. Phased array coils are useful to

image the whole of the cervical and thoracic cord whilst maintaining optimum SNR and resolution.

Spatial resolution is important especially in axial/oblique images, as the nerve roots in the thoracic region are commonly difficult to visualize. Thin slices with a small gap and relatively fine matrices are implemented to maintain spatial resolution. Multiple NEX/NSA are also advisable if the inherent SNR is poor. Therefore, unless FSE is utilized, scan times are usually of several minutes duration.

Fortunately, a rectangular/asymmetric FOV is used very effectively in sagittal imaging as the thoracic spine fits into a rectangle with its longitudinal axis running S to I. This facilitates the acquisition of fine matrices in short scan times. With a reduced FOV in the phase direction, aliasing may be a problem. In sagittal imaging, this artefact originates from the anterior chest wrapping into the FOV. Increasing the size of the overall FOV or utilizing oversampling (if available) may eliminate or reduce this artefact. In addition, spatial presaturation pulses brought into the FOV are effective (see *Flow phenomena and artefacts* in Part 1). In practice, as a fairly large FOV is used to image the thoracic spine and there is signal fall-off in the anterior part of the chest, aliasing is not usually troublesome.

The multiple 180° RF pulses used in FSE sequences cause lengthening of the T2 decay time of fat so that the signal intensity of fat on T2 weighted FSE images is higher than in CSE. This sometimes makes the detection of marrow abnormalities difficult. Therefore, when imaging the vertebral bodies for metastatic disease, a STIR sequence should be utilized.

9

Artefact problems

Flow from CSF pulsations commonly causes severe phase ghosting in the thoracic region, although the speed of flow is often less than in the cervical area. Spatial presaturation pulses placed S and I to the FOV are necessary to reduce these flow-related problems. GMN also minimizes flow artefact but, as it increases the signal from CSF and the minimum TE available, it is usually reserved for T2 and T2* weighted sequences. FSE is commonly utilized in this area as the associated scan time reduction enables the implementation of very fine matrices. However, this sequence often demonstrates increased flow artefact compared with SE and GRE sequences. Therefore, if flow artefact is too troublesome, SE or GRE may be substituted.

Phase ghosting from cardiac and respiratory motion is the main source of artefact in the thoracic region. Spatial presaturation pulses brought into the FOV and placed over the heart and lung fields are very effective at reducing this. Pe gating minimizes artefact even further but, as the scan time is dependent on the patient's heart rate, it is sometimes time-consuming. The implementation of Pe gating is therefore best reserved for cases of severe flow artefact that cannot be reduced to tolerable levels by other measures.

In sagittal imaging, swapping the phase axis so that it runs from S to I instead of A to P removes the artefact from the cord. However, if there is significant kyphosis, the artefact may still obscure the cervical and lumbar regions. In addition, if a rectangular/asymmetric FOV is implemented, swapping the phase axis places the longitudinal axis of the rectangle horizontally so that its benefits cannot be utilized. On newer systems it is possible to use curved spatial presaturation pulses so that accurate placement of bands over the thoracic aorta is possible.

Due to the implementation of a small FOV in axial/oblique imaging, aliasing commonly occurs and therefore oversampling is necessary. In addition, phase artefact from movement of the lateral walls of the chest during respiration, and some vessel pulsation, often interferes with the images. Careful placement of spatial presaturation pulses A, R, and L of the FOV is usually effective at reducing this. RC is rarely necessary in the thoracic spine because the posteriorly situated spinal coil causes signal fall-off from the anterior chest wall, and therefore respiratory artefact is usually less troublesome than when imaging the whole chest in the body coil. Movement of the diaphragm is more significant, however, and RC may be considered if this is a particular problem.

Patient considerations

Patients with cord trauma may be severely disabled and in great pain. The examination should obviously be undertaken as speedily as possible under these circumstances. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

9

Contrast usage

Contrast is not routinely given for disc disease. However, in cases of leptomeningeal spread of certain tumours such as medulloblastoma, contrast is invaluable. Other cord lesions such as ependymomas and pinealoblastomas also enhance well with contrast, as do infectious processes and active MS plaques. Bony tumours, especially those that return a low signal on T1 weighted images, enhance with contrast but this often increases their signal intensity so that they are isointense with the surrounding vertebra. Under these circumstances, chemical/spectral presaturation or the Dixon technique should be implemented to reduce the signal from fatty marrow in the vertebral bodies. STIR should not be used in conjunction with contrast, as its inverting pulse may nullify the signal from the tumour that, as a result of contrast enhancement, now has a similar T1 recovery time to fat.

Lumbar spine

Common indications

- Disc prolapse with cord or nerve root compression.
- Spinal dysraphism (to assess cord termination, syrinx, diastemato-myelia).
- Discitis.
- Evaluation of the conus in patients with appropriate symptoms.
- Failed back syndrome.
- Arachnoiditis.

Equipment

- Posterior spinal coil/multi-coil array spinal coil.
- Foam pads to elevate the knees.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with their knees elevated over a foam pad, for comfort and to flatten the lumbar curve so that the spine lies nearer to the coil. The coil should extend from the xiphisternum to the bottom of the sacrum for adequate coverage of the lumbar region. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes just below the lower costal margin, which corresponds to the third lumbar vertebra.

Suggested protocol

Sagittal/coronal SE/FSE T1 or coherent GRE T2*

Acts as a localizer if three-plane localization is unavailable. The coronal or sagittal planes may be used.

Coronal localizer: Medium slices/gap are prescribed relative to the vertical alignment light, from the posterior aspect of the spinous processes to the anterior border of the vertebral bodies. The area from the conus to the sacrum is included in the image.

P 20 mm to A 30 mm

Sagittal localizer: Medium slices/gap are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of the vertebral bodies. The area from the conus to the sacrum is included in the image.

L 7 mm to R 7 mm

Figure 9.13 Sagittal FSE T1 weighted midline slice through the lumbar spine showing normal appearances.

9

Sagittal SE/FSE T1 (Figure 9.13)

Thin slices/gap are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of the vertebral bodies (unless the paravertebral region is required). The area from the conus to the sacrum is included in the image.

L 22 mm to R 22 mm

Sagittal SE/FSE T2 or coherent GRE T2* (Figure 9.14)

Slice prescription as for Sagittal T1.

Axial/oblique SE/FSE T1/T2 or coherent GRE T2* (Figure 9.16)

Thin slices/gap are angled so that they are parallel to each disc space and extend from the lamina below to the lamina above the disc. The lower three lumbar discs are commonly examined (Figure 9.15).

Figure 9.14 Sagittal FSE T2 weighted midline slice through the lumbar spine showing normal appearances.

Figure 9.15 Sagittal FSE T2 weighted midline slice showing slice prescription boundaries and orientation for axial/oblique imaging of lumbar discs.
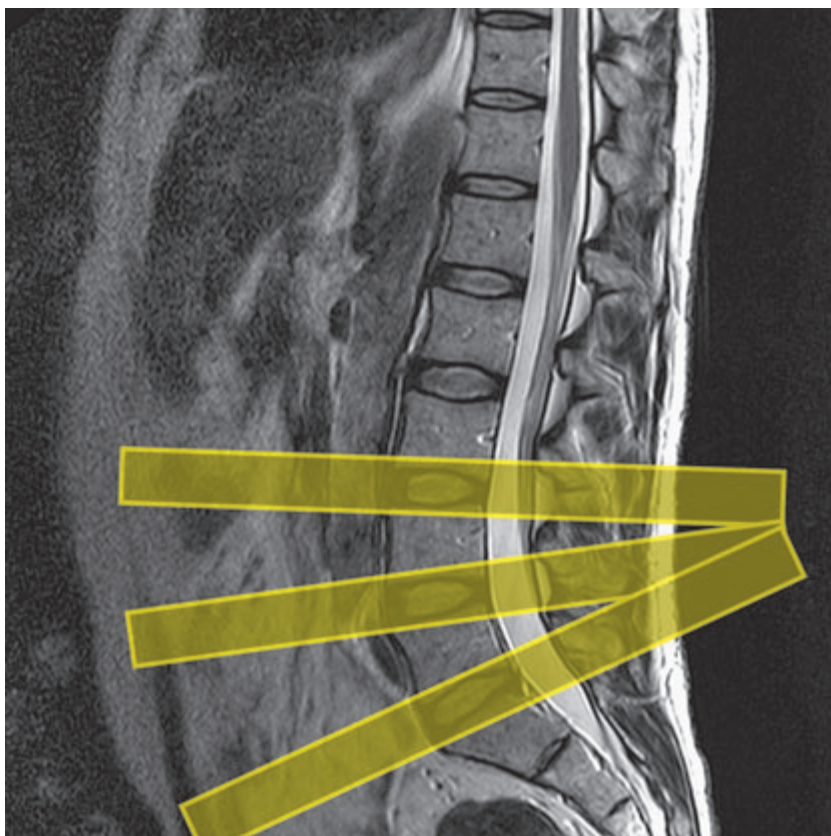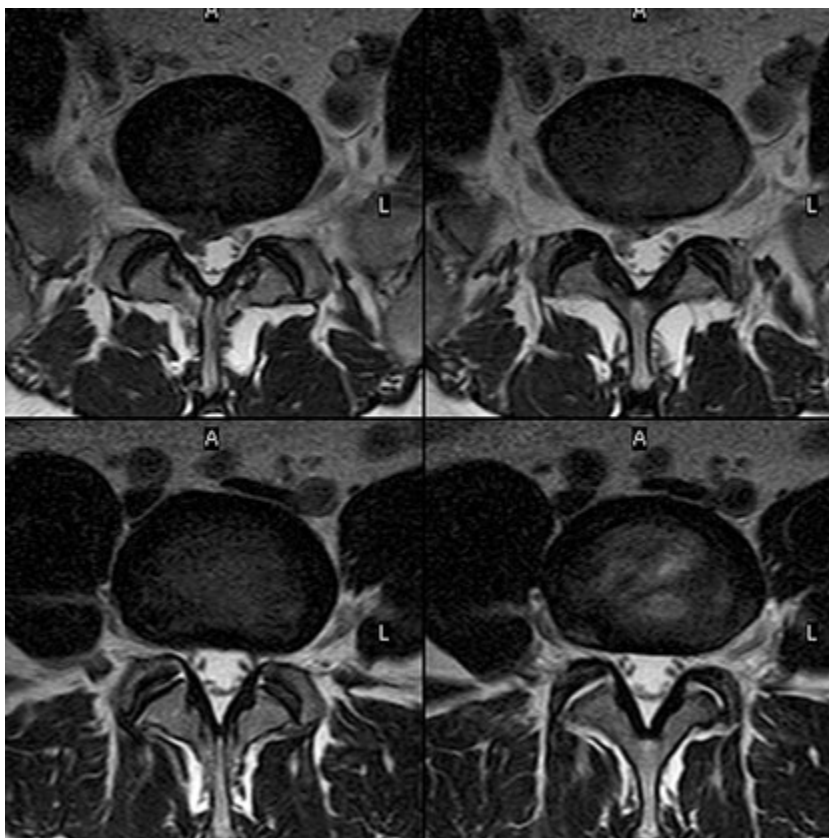
Figure 9.16 Axial/oblique FSE T2 weighted image of the lumbar spine.

Additional sequences

Axial/oblique or Sagittal SE/FSE T1

With contrast for determining disc prolapse versus scar tissue in failed back syndrome, and for some tumours. Without contrast in spinal dysraphism. Chemical/spectral presaturation is beneficial to differentiate between fat and enhancing pathology.

Coronal SE/FSE T1

For cord tethering or alternative view of conus when sagittals are inconclusive.

Axial/oblique FSE T2

For arachnoiditis. As for Axial/obliques, **except** prescribe one slice through, and parallel to, each disc space and vertebral body from the sacrum to the conus (Figure 9.17).
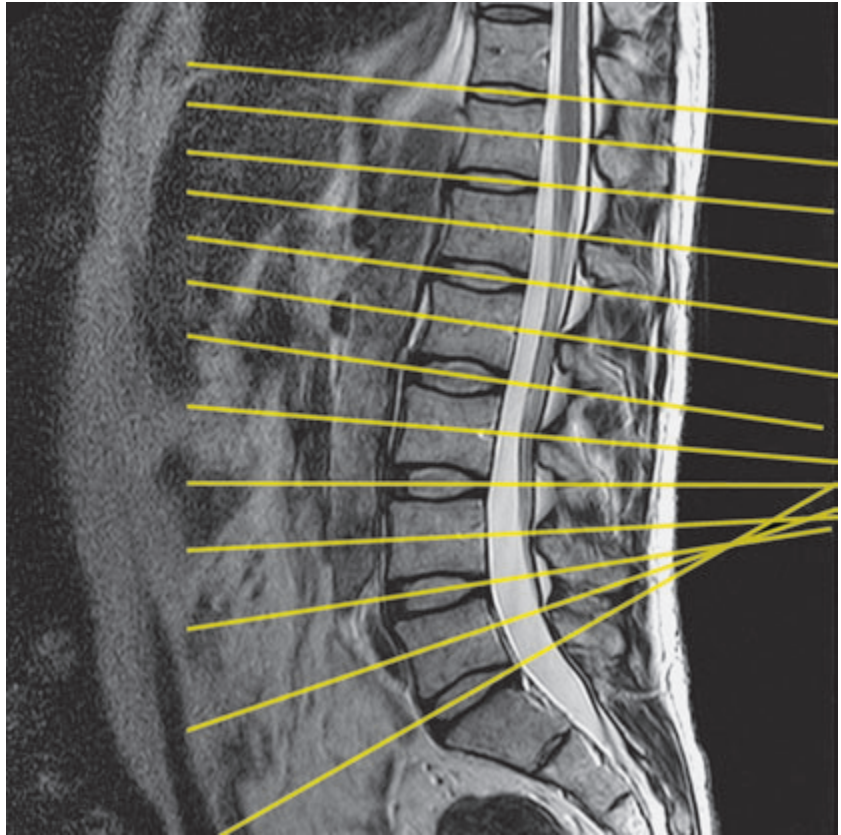
Figure 9.17   Sagittal FSE T2 weighted image of the lumbar spine showing axial/oblique slice prescription for arachnoiditis.

9

STIR

While FSE sequences provide excellent T2 weighted images of the spine, the signal intensity from the normal fat in the marrow of the vertebral bodies is generally high, even with longer TE times. For that reason, marrow pathology, such as tumours or fractures, may not be adequately visualized on T2 weighted FSE sequences. A STIR sequence can be utilized to visualize bone marrow abnormalities better. This is demonstrated in the images in Figures 9.18–9.20. The T1 weighted FSE shows an acute fracture of the L-1 vertebral body. The T2 weighted FSE also shows the fracture but the majority of the bone marrow signal in the L1 vertebral body appears similar to the other vertebral bodies. The STIR clearly shows the increased signal within the L1 vertebral body consistent with an acute fracture.

Image optimization

Technical issues

The SNR in the lumbar region depends on the quality of the coil. Posterior spinal coils return high signal in the area of the lumbar canal and vertebral

Figure 9.18 Sagittal T1 weighted FSE showing an acute fracture in the body of L1.

Figure 9.19 Sagittal T2 weighted FSE of the same patient shown in Figure 9.18.

9

Figure 9.20   Sagittal FSE-STIR of the same patient shown in Figure 9.18.

bodies, but flare from the fatty tissues in the buttocks sometimes interferes with the image. Phased array coils allow for imaging of the thoracic and lumbar spine in conjunction with good SNR and resolution. As CSF flow is reduced in this area, FSE is routinely used. This enables the implementation of very fine matrices so that spatial resolution is significantly increased. Resolution is also maintained by using rectangular/asymmetric FOV in sagittal imaging (with the long axis of the rectangle running from S to I), and a small FOV in axial/oblique imaging. Fine matrices are especially necessary in arachnoiditis to detect nerve root clumping.

Artefact problems

CSF pulsation is not usually troublesome as the speed of flow is relatively slow. However, phase artefact from the aorta and the inferior vena cava (IVC), and lateral flow from the lumbar vessels, sometimes obscures the lumbar canal. Spatial presaturation pulses brought into the FOV and placed S, I and A in the sagittal images, and A, R and L in the axial/oblique images, reduce phase ghosting. GMN minimizes flow artefact even further but, as it increases the signal in CSF and the minimum TE available, it is mainly reserved for the T2 and T2* weighted sequences.

Figure 9.21 Sagittal FSE T1 weighted images of the lumbar spine with phase A to P (left) and S to I (right). The definition of the spinal cord is clearly improved on the right-hand image.

9

Swapping the phase axis in sagittal imaging so that it runs from S to I instead of A to P is probably the best way of removing this artefact from the cord. However, a rectangular/asymmetric FOV cannot be used under these circumstances as the long axis of the rectangle is placed horizontally (Figure 9.21). A compromise is to swap the phase axis and not use a rectangular/asymmetric FOV in the T1 sagittal image, and keep the phase axis AP and use a rectangular/asymmetric FOV in the T2 sagittal image.

With a reduced FOV in the phase direction, aliasing may be a problem. In sagittal imaging, this artefact originates from the buttocks and abdomen wrapping into the FOV (Figure 9.22). Increasing the size of the overall FOV or utilizing oversampling (if available) may eliminate or reduce this artefact. If the phase axis is swapped, aliasing occurs as the areas superior and inferior to the coil are wrapped into the FOV and therefore oversampling is necessary to avoid this. In addition, owing to the implementation of a small FOV in the axial/oblique imaging, aliasing commonly occurs and therefore oversampling is also required in this plane. Spatial presaturation pulses brought into the FOV are also effective (Figure 9.23).

Figure 9.22 Sagittal FSE T2 weighted midline slice through the lumbar spine using rectangular/asymmetric FOV. Note phase aliasing from the buttocks (arrow).

Figure 9.23 Correct placement of spatial pre-saturation bands when using rectangular/asymmetric FOV in the lumbar spine.
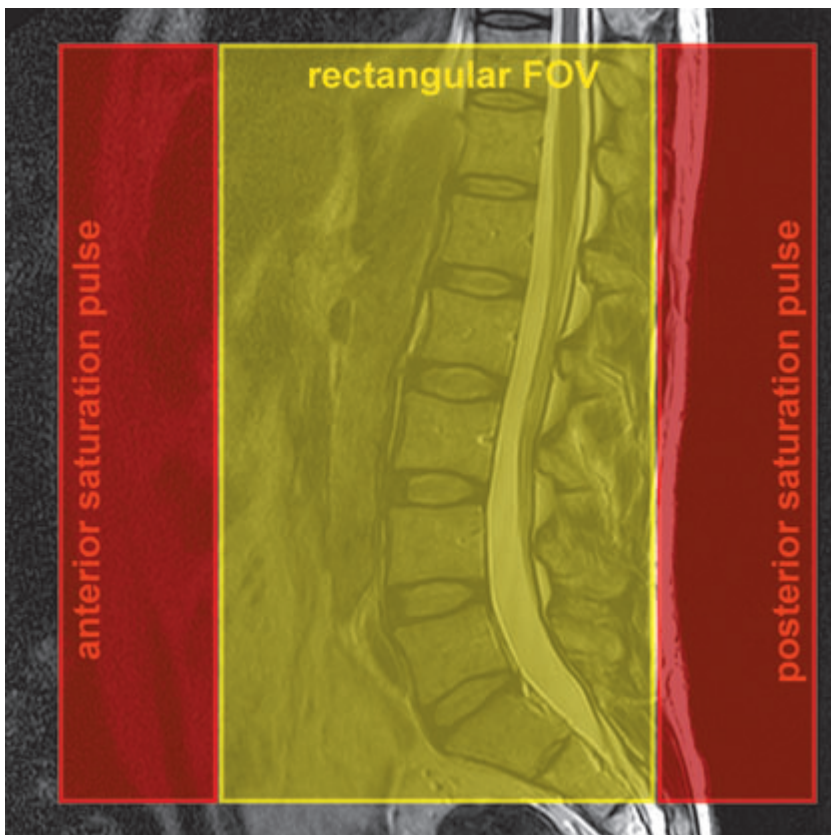
The multiple 180° RF pulses used in FSE sequences cause lengthening of the T2 decay time of fat so that the signal intensity of fat on T2 weighted FSE images is higher than in CSE. This sometimes makes the detection of marrow abnormalities difficult. Therefore, when imaging the vertebral bodies for metastatic disease, a STIR sequence should be utilized.

Patient considerations

Many patients are in severe pain especially if they are suffering from a prolapsed lumbar disc. Make the patient as comfortable as possible with pads supporting their knees in a slightly flexed position. Small pads placed in the lumbar curve often help to alleviate sciatica and other types of back pain.

Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is used to distinguish disc prolapse from scar tissue post-operatively in failed back syndrome. These images are acquired with or without chemical/spectral presaturation. STIR should not be used with contrast enhancement, as the contrast reduces the T1 value of damaged tissues so that it is similar to that of fat, and is therefore nullified by the inverting pulse. Scar tissue enhances immediately after the injection, but disc material does not. However, about 20–30 min after the injection, disc material also enhances and therefore scanning should not be delayed after the administration of contrast. In addition, the epidural veins and granulation tissue at the periphery of a disc and fibrosis may enhance. Contrast is also invaluable to visualize suspicious lesions in the conus.

9

Whole spine imaging

Common indications

- Cord compression (level unknown), due to metastatic disease or primary cord tumour.
- Bone marrow screening.
- Congenital abnormalities of spinal curvature (scoliosis and kyphosis).
- Evaluation of the extent of a syrinx.
- Leptomeningeal disease.

Equipment

- Body coil/multi-coil array spinal coil.
- Pe gating leads if required.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the sacrum and the base of the skull (which corresponds to about 2 cm below the sternal notch). Pe gating leads are attached if required.

Suggested protocol

Sagittal SE/FSE T1 (Figure 9.24(a))

Thin slices/gap are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of vertebral bodies (or prescribed graphically from a coronal localizer).

L 22 mm to R 22 mm

Include the entire canal from the base of the skull to below the sacrum and use the largest FOV available. Repeat the scan if an area is missed. If severe scoliosis is present, coronal images may be more beneficial than sagittals to assess the direction and extent of the curvature.

Sagittal SE/FSE T2 or coherent GRE T2* (Figure 9.24(b))

Slice prescription as for Sagittal T1.

Figure 9.24 Sagittal FSE T1 weighted image (left) and T2 weighted image (right) of the cervical and thoracic cord imaged using a phased array coil.

9
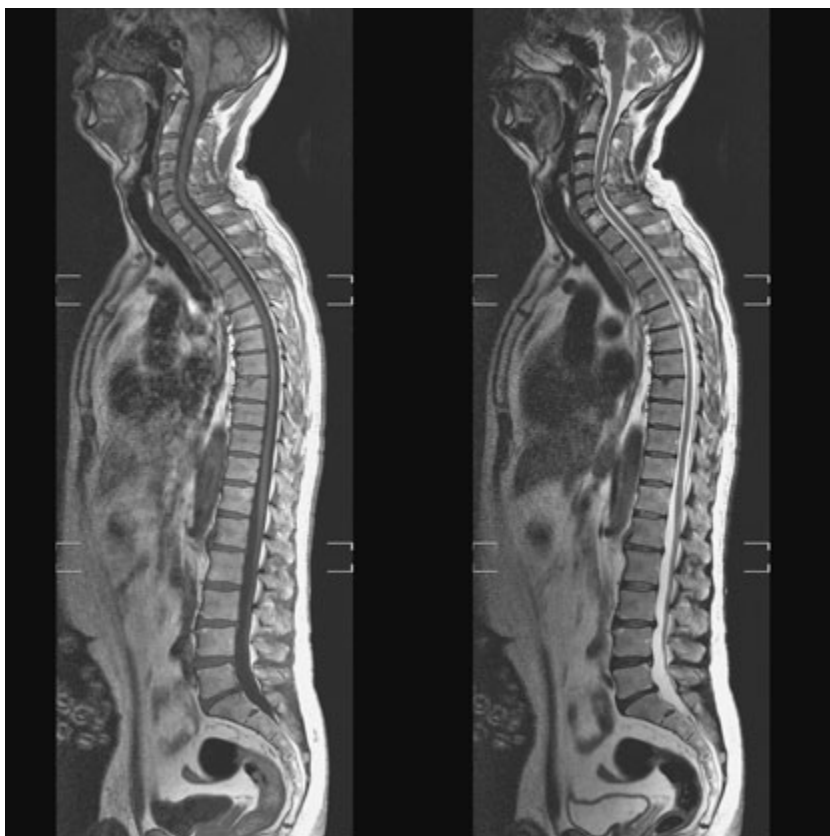
Axial/oblique SE/FSE T1/T2

Thin slices/gap are prescribed through the ROI. Use a smaller local coil once the ROI has been established (not necessary with a multi-coil array). In patients with severe spinal curvature, obliques may be performed to achieve orthogonal images.

Additional sequences

Sagittal SE/FSE T2 or STIR

For bone marrow screening, include the sternum in the image and add coronals of the bony pelvis. Use chemical/spectral presaturation pulses in SE/FSE sequences.

Sagittal/oblique SE/FSE T1

With contrast for tumour infection and leptomeningeal disease.

Figure 9.25 Sagittal oblique balanced GRE through the cervical cord showing nerve roots and peripheral nerves.

9

MR myelography/neurography (Figure 9.25)

Examination of nerve roots and peripheral nerves with high-resolution imaging are useful additional techniques.

Image optimization

Technical issues

These examinations are often carried out to establish the level and cause of a cord compression. Therefore, spatial resolution is not necessarily as important as a quick diagnosis. The level of the compression may be unknown, and therefore coverage of the whole spinal canal is the most important consideration. In the past this could only be achieved with the body coil, as surface coils did not cover the entire spine. However, phased array coils have now been introduced that give the benefits of maximum coverage and optimum SNR. If phased array coils are unavailable, the body coil is implemented. This results in a loss of overall SNR and poor local spatial resolution, as a large FOV is utilized to cover the whole spine.

Once a level has been established, the body coil may be substituted for a surface coil and higher-quality images obtained. This strategy is unnecessary when using a multi-array as the increase in SNR enables acquisition of images with adequate resolution. With both coil types, a rectangular/asymmetric FOV is used in the sagittal images to improve spatial resolution with the long axis of the rectangle S to I.

Artefact problems

When imaging the entire spine with the body coil, artefacts are caused by CSF flow, heart and great vessel motion, and respiration. Spatial presaturation pulses placed S and I to the FOV reduce CSF artefact. They are often also placed over the heart and great vessels but can obscure some of the spine if there is spinal curvature. However, on newer systems it is possible to use curved spatial presaturation pulses that enable accurate placement of the bands over the aorta. Spatial presaturation pulses are commonly less effective over a large FOV and therefore phase ghosting may still be evident. In addition, if chemical/spectral presaturation is employed, it may be less effective than with a small FOV. This is because the energy of the presaturation pulse is now delivered to a greater volume of tissue, thereby reducing its effectiveness. Additional shimming may be required before chemical/spectral presaturation sequences.

   GMN also minimizes flow artefact but, as it increases signal in CSF and the minimum TE available, it is usually only beneficial in T2 and T2* weighted sequences. Pe gating minimizes artefact even further but, as the scan time is dependent on the patient's heart rate, it is sometimes time-consuming. The implementation of Pe gating is therefore best reserved for cases of severe flow artefact that cannot be reduced to tolerable levels by other measures.

   The multiple 180° RF pulses used in FSE sequences cause lengthening of the T2 decay time of fat so that the signal intensity of fat on T2 weighted FSE images is higher than in CSE. This sometimes makes the detection of marrow abnormalities difficult. Therefore, when imaging the vertebral bodies for metastatic disease, a STIR sequence should be utilized.

9

Patient considerations

Patients with cord compression are sometimes severely disabled and in extreme pain. A swift examination is often necessary to avoid patient movement. An analgesic administered prior to the examination may be beneficial. Patients with severe curvature of the spine often find it impossible to lie flat on the examination couch. Patient comfort is very important as these examinations are sometimes lengthy due to the extra sequences needed to achieve orthogonal images. It is wise to let the patient assume the most comfortable position and use foam pads to support them. The plane of the images is then adjusted to their position. Sometimes the lung field area of these patients is compromised and respiration may become

an effort when they lie supine. Oxygen can be administered to the patient during the examination, but reducing the scan time as much as possible is probably the best remedy for this problem.

Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is often necessary especially for leptomeningeal disease, intradural or extramedullary lesions and metastases. It may also be useful for spinal osteomyelitis.

9

10

Chest

10

Table 10.1 Summary of parameters. The figures given are general and should be adjusted according to the system used (Table 2.1)

Spin echo (SE)

short TE	min to 30 ms
long TE	70 ms +
short TR	300−600 ms
long TR	2000 ms +

Fast spin echo (FSE)

short TE	min−20 ms
long TE	90 ms +
short TR	400−600 ms
long TR	4000 ms +
short ETL	2−6
long ETL	16 +

Inversion recovery (IR) T1

short TE	min−20 ms
long TR	3000 ms +
medium TI	200−600 ms
short ETL	2−6

STIR

long TE	60 ms +
long TR	3000 ms +
short TI	100−175 ms
long ETL	12−20

FLAIR

long TE	60 ms +
long TR	3000 ms +
long TI	1700−2200 ms
long ETL	12−20

Coherent GRE

long TE	15 ms +
short TR	≤ 50 ms
flip angle	20°−40°

Incoherent GRE

short TE	min−5 ms
short TR	≤ 50 ms
flip angle	20°−40°

Balanced GRE

TE	minimum
TR	minimum
flip angle	≥ 40°

SSFP

TE	minimum
TR	40−50 ms
flip angle	20°−40°

Slice thickness

2D	thin	2−4 mm
	medium	5−6 mm
	thick	8 mm
3D	thin	≤ 1 mm
	thick	≥ 3 mm

FOV

small	≤ 18 cm
medium	18−30 cm
large	≥ 30 cm

NEX/NSA

short	≤ 1
medium	2−3
multiple	≥ 4

Slice numbers

Volumes	small	≤ 32
	medium	64
	large	≥ 128

Matrix (frequency × phase)

coarse	256 × 128 or 256 × 192
medium	256 × 256 or 512 × 256
fine	512 × 512
very fine	≥ 512 × 512

PC-MRA

2D and 3D	TE	minimum
	TR	25−33 ms
	flip angle	30°
VENC venous	20−40 cm/s	
VENC arterial	60 cm/s	

TOF-MRA

2D	TE	minimum
	TR	28−45 ms
	flip angle	40°−60°
3D	TE	minimum
	TR	25−50 ms
	flip angle	20°−30°

10

Lungs and mediastinum

Basic anatomy (Figure 10.1)
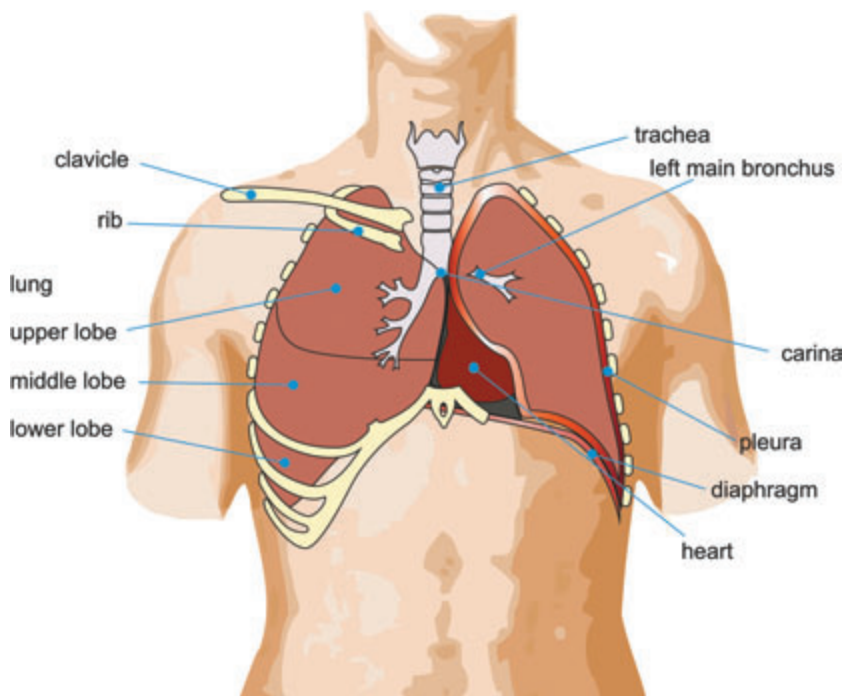
Figure 10.1 Anterior view of the components of the chest cavity.

Common indications

- Mediastinal lymphadenopathy.
- Central and superior sulcus bronchial tumours.
- Distinction between neoplasm and consolidated lung.
- Alternative to CT of the mediastinum and chest wall when the patient is hypersensitive to contrast medium.
- Vascular evaluation of aortic dissection, pulmonary embolus, aortic aneurysm or vascular stenosis.
- Lung perfusion studies.
- Assessment of diaphragmatic motion.

Equipment

- Body coil/volume torso multi-coil array.
- RC bellows.
- ECG or peripheral gating leads.
- Ear plugs or headphones.

10

Patient positioning

The patient lies supine on the examination couch with the RC bellows (if required) and ECG gating leads attached. Pads can be placed under the patient's knees (for comfort) and beside the patient's elbows (for optimal MR imaging). In some cases, if the patient is not comfortable supine and/or if the patient has trouble in confined spaces, prone positioning may be a suitable alternative.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the fourth thoracic vertebra, or the nipples. The patient can be placed feet first into the magnet if the ECG trace is unsatisfactory as this changes the patient's polarity relative to the main field (see *Gating and respiratory compensation techniques* in Part 1).

Suggested protocol

Coronal breath-hold fast incoherent (spoiled) GRE/SE T1 (Figure 10.2)

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Medium slices/gap are prescribed relative to the vertical

10
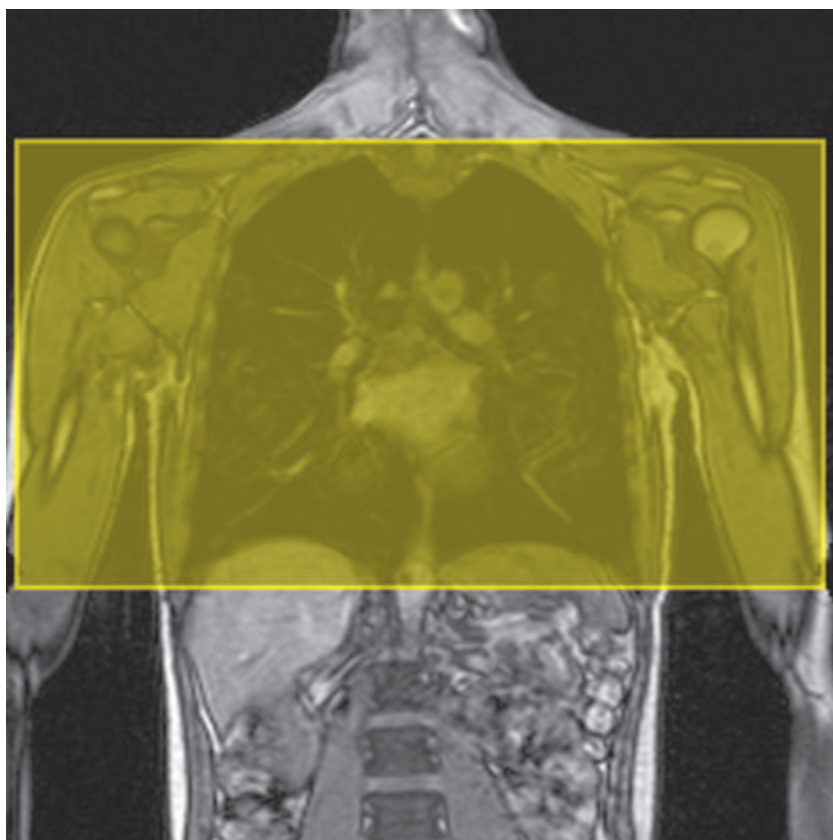
Figure 10.2 Coronal breath-hold incoherent (spoiled) GRE T1 of the chest showing prescription of axial slices.
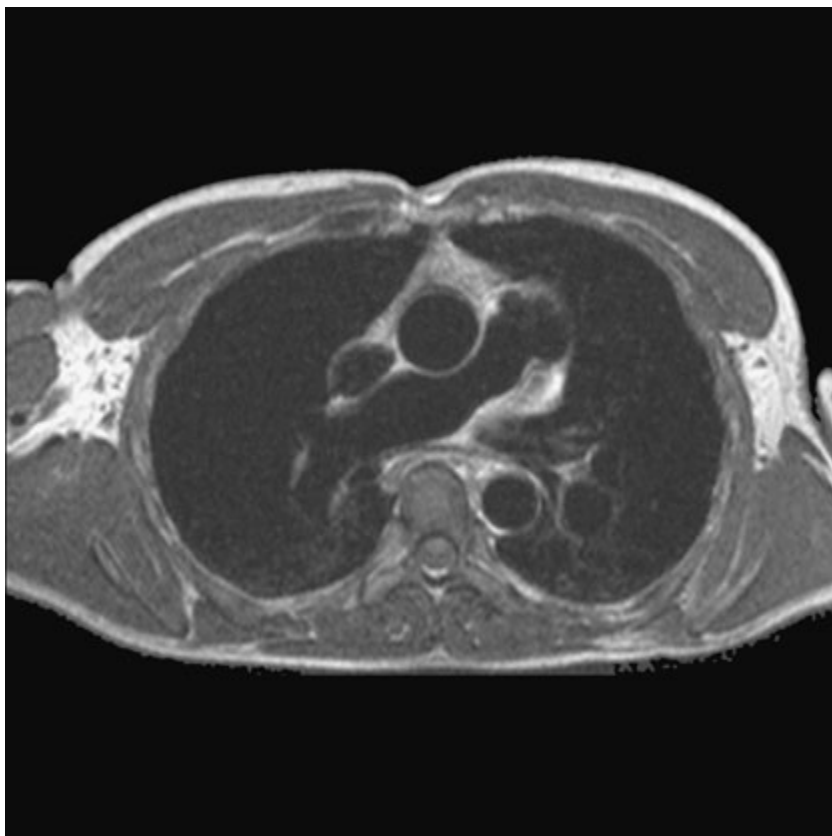
Figure 10.3 Axial SE T1 weighted gated image of the chest or axial imaging.

10

alignment light, from the posterior chest muscles to the sternum. The entire lung fields from apex to base are included in the image. As the chest anatomy is generally located more anteriorly than posteriorly, slices are offset in the anterior direction.

P 60 mm to A 80 mm

Axial FSE T1/incoherent (spoiled) GRE T1 (Figures 10.3–10.5)

As for the Coronal T1, **except** slice thickness/gap is adjusted to fit the ROI. Prescribe slices from the diaphragm to the apex of the lung or through the ROI.

Axial FSE PD/T2/SS-FSE T2/GRE T2* (Figure 10.6)

Slice prescription as for Axial T1.
   Useful to characterize active tissue such as distinguishing tumour from consolidated lung and to evaluate fluid pneumonia or pleural effusion.
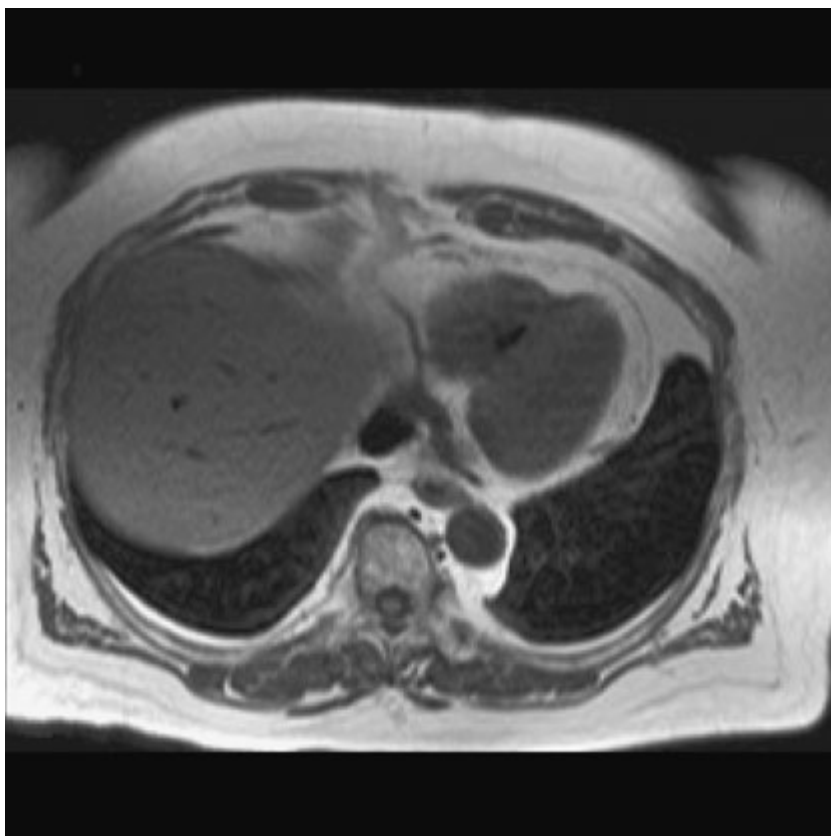
Figure 10.4 Axial FSE T1 weighted image through the chest showing a large lesion in the left lung.
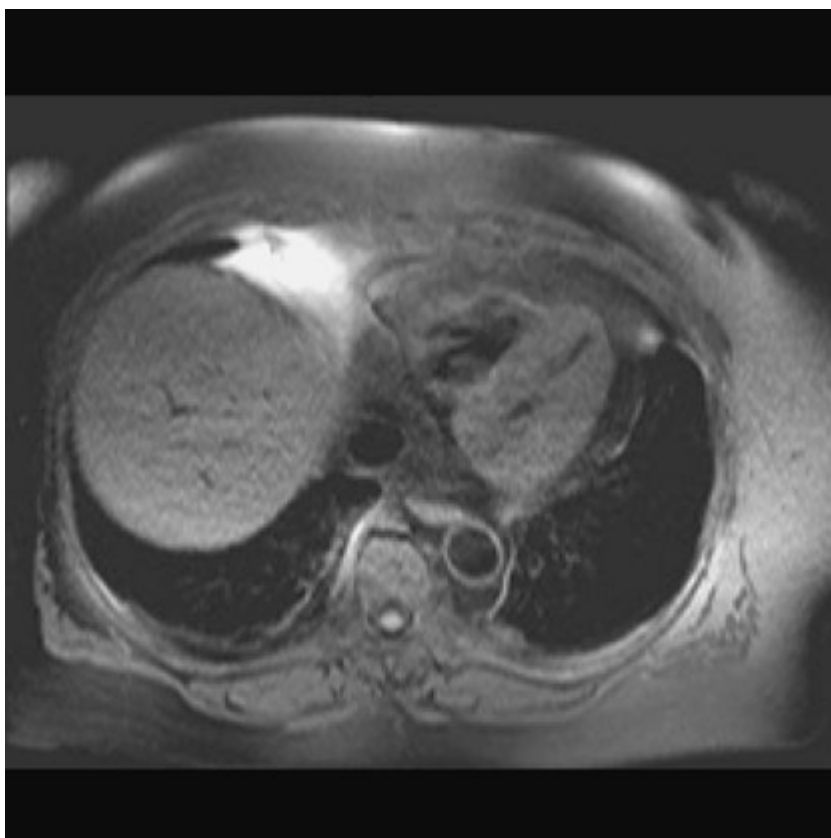
Figure 10.5 Axial incoherent GRE T1. Same slice as Figure 10.4.

Figure 10.6 Axial SS-FSE. Same slice as shown in Figure 10.4.

Additional sequences

Perfusion studies

Lung perfusion can be evaluated by either administering contrast or with 'spin tagged perfusion' techniques. In these cases contrast is 'tagged' with either contrast or arterial spin tagging applied in the midline of the patient in an attempt to saturate blood flowing from the heart and into the lungs by way of the pulmonary arteries.

Ventilation studies

This study is analogous to the VQ scan offered in Nuclear Medicine. The patient breathes in hyperpolarized helium gas and holds their breath, while images are acquired.

Coronal fast incoherent (spoiled) GRE T1/SS-FSE T2

These sequences can be used during respiration to assess motion of the diaphragm. In this case, slices are acquired during normal respiration and replayed as a movie or cine loop.

10

Image optimization

Technical issues

The chest has a relatively poor SNR as the proton density of the lung fields is low. In addition, there is little fat to give good contrast. The implementation of a volume array coil helps maintain SNR. This is especially useful when thinner slices and a finer matrix are required. Chest imaging can be performed with a number of RF coil designs. Although the body coil is notorious for lower SNR, it can be utilized for large areas of coverage. Also, the body coil is acceptable in cases where contrast is the main determining factor in image contrast, such as MRA of the aorta or the pulmonary arteries. For the most part therefore the body coil will produce optimum images for chest imaging. For higher SNR, higher resolution torso array coils should be used (see *Heart and great vessels*).

The use of multiple NEX/NSA not only reduces some respiratory and cardiac artefact because of signal averaging, but also improves the SNR due to increased data collection. The disadvantage of this strategy is the associated increase in scan time, although this can be compensated for, to some degree, by the implementation of a coarser matrix or a rectangular/asymmetric FOV. SE T1 weighted sequences are traditionally used to show anatomy and black blood. GRE sequences are useful for the evaluation of flow, and T2 weighted sequences demonstrate pathology and free fluid. On some systems FSE is not compatible with RC techniques that use phase reordering. Under these circumstances SE sequences can be substituted.

Artefact problems

Respiratory, cardiac and flow motion are the most obvious artefacts in the chest. Image quality can be compromised by physiologic motion from the lungs and heart, from flowing blood within vessels and, in some cases, from the oesophagus and stomach. Compensation for physiologic motion artefacts in the chest can be reduced by a number of imaging options including: respiratory compensation, breath-hold techniques, cardiac gating, cardiac triggering or other imaging options (saturation pulses or gradient moment nulling). Breath-hold techniques are achieved by the acquisition of rapid imaging sequences (20 seconds or less) and instructing the patient to hold their breath during the image acquisition.

Motion artefact will always occur along the phase encoding axis, and the degree to which they interfere with the image is mostly due to the proficiency of the respiratory compensation techniques used and ECG gating. For respiratory gating and/or respiratory triggering, a respiratory monitoring device, known as a bellows is placed around the patient's chest or abdomen. Placement can be determined by the patient's breathing style. If, for example patient respiratory motion is generated by motion in the chest, then the bellows should be placed there. However, if the patient's motion occurs more within the abdomen, the bellows should be located in the abdominal region. (For more information about

10

bellows placement, *see Respiratory compensation techniques* in Part 1). Alternatively, breath-hold techniques may be used to suspend respiration. Check that the ECG leads are correctly attached and that the ECG trace has good amplitude and is triggering correctly (see *Gating and respiratory compensation techniques* in Part 1). When implemented properly, ECG gating effectively reduces cardiac motion artefact. However, if ECG gating is inefficient, image quality is compromised.

The phase encoding direction is generally prescribed by the system and thus defaults along a given direction. For the most part, the phase direction defaults along the short axis of the anatomy. Therefore the phase encoding axis usually lies A to P on axial images and R to L on coronals. Swapping the phase axis to R to L on the axial scans and S to I on coronals is occasionally beneficial to remove artefact from the area of interest. For example, the phase direction for axial chest imaging generally defaults to a position anterior to posterior direction. However, if the motion artefact 'streaks' across anatomy or pathology of interest, swapping phase and frequency directions can be selected to 'relocate' the motion artefact to a position right to left across the image (Figures 10.7 and 10.8). As this strategy positions the long axis of the anatomy along the phase axis, oversampling is necessary to avoid aliasing. Furthermore, caution should

10
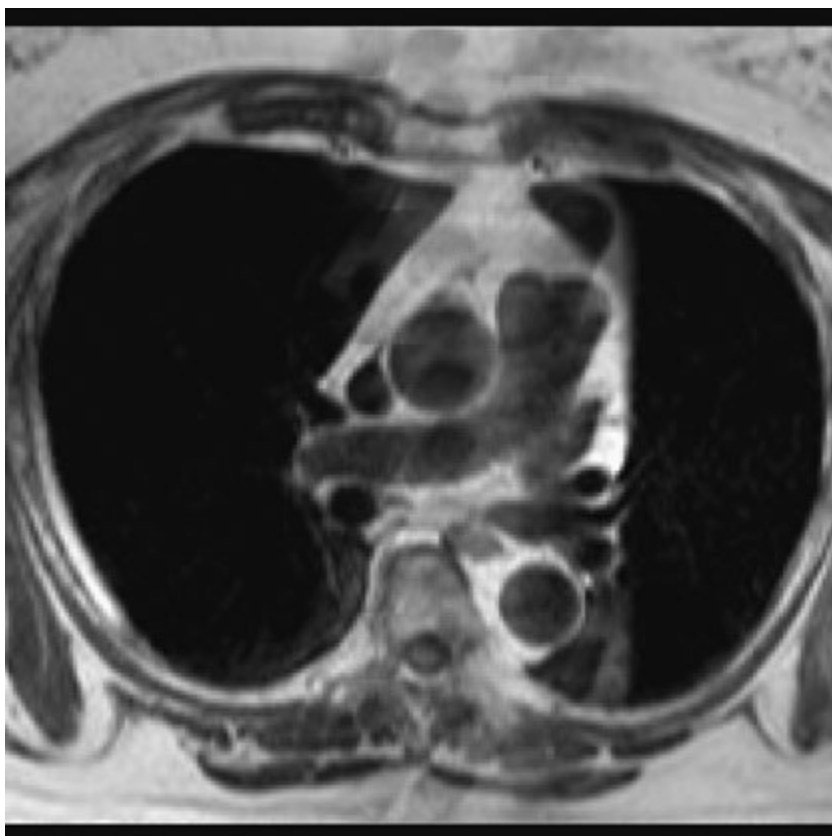
Figure 10.7 Axial FSE T1 weighted image of the chest with phase anterior to posterior.
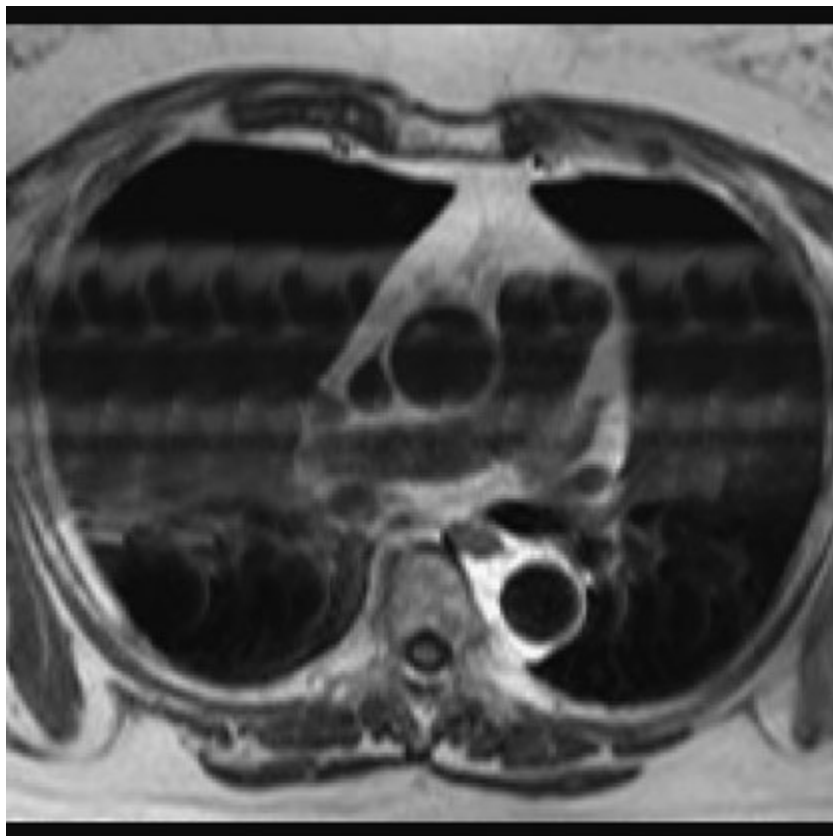
Figure 10.8 Axial FSE T1 weighted image of the chest with phase left to right.

be used if rectangular FOV has also been selected as the short axis of the rectangle is located along the phase direction. Therefore as the phase direction is swapped, so is the direction of the rectangle.

Spatial presaturation pulses are also important to reduce flow artefact further. They are placed S and I to the FOV to decrease artefact from the aorta and IVC. R and L spatial presaturation pulses are beneficial in coronal images to decrease artefact from venous flow entering the chest from the subclavian vessels. In addition, when used in conjunction with SE or FSE sequences, spatial presaturation pulses produce black blood (see Figure 10.18). If signal persists in a vessel it may indicate either slow flow or occlusion. GMN reduces flow artefact further but, as it also increases the signal in vessels and the minimum TE available, it is not usually beneficial in T1 weighted sequences unless contrast agents have been administered. When used in conjunction with GRE sequences, GMN produces bright blood (see Figure 10.18). If low signal is seen within the vessel, it may indicate either slow flow or occlusion. In addition consideration should be given to the fact that when a structure is bright and it moves during MR image acquisition, it can 'streak' across the MR image in the phase direction.

Patient considerations

Patients having this kind of investigation are often breathless; therefore minimizing the scan time is important. However, if the patient has a slow heart rate or a poor cardiac output, the system cannot always trigger off every R wave, thereby lengthening the scan time considerably. Under these circumstances limiting the number of sequences is beneficial, and continuous reassurance of the patient may steady their heart rate and respiration. In addition, patient monitoring is recommended for patients who are short of breath and the administration of oxygen may be required. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast can be given to enhance lung, mediastinal or hilar masses. This may be helpful to increase the conspicuity of pathology in an area with low inherent contrast and to visualize pleural inflammation. Contrast can also be useful for visualizing chest vessels. Gaseous agents such as hyper-polarized helium gas are under investigation for the evaluation of lung ventilation during inhalation.

10

Heart and great vessels

Basic anatomy (Figure 10.9)
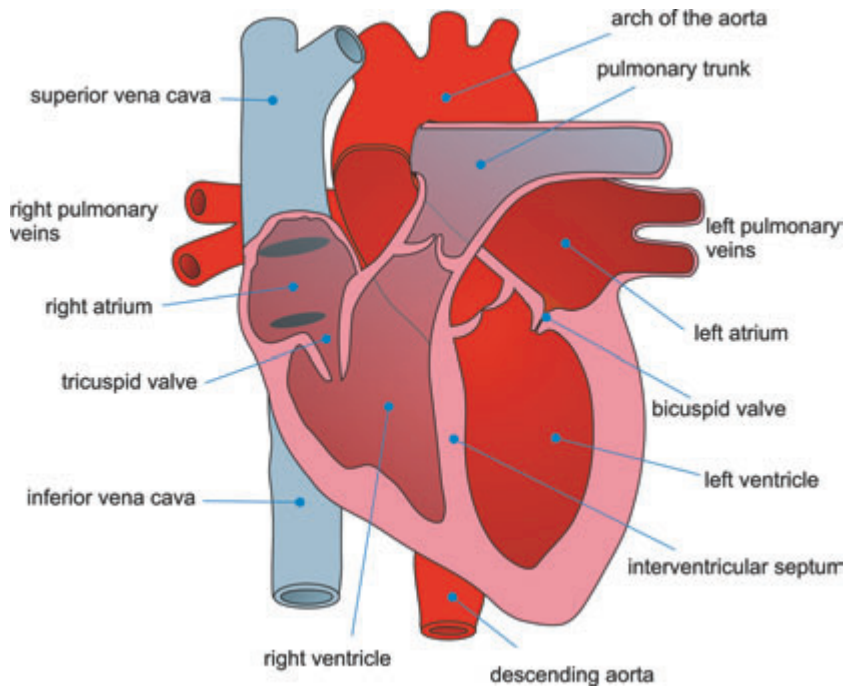
Figure 10.9 The great vessels and chambers of the heart.

Common indications

- Thoracic aortic aneurysm, dissection, and coarctation.
- Complex congenital abnormalities of the heart and great vessels.
- Atrial or ventricular septal defect.
- Assessment of ventricular function.
- Assessment of ventricular muscle mass.
- Vessel patency and thrombus.
- Valvular dysfunction.

Equipment

- Body coil/volume torso array coil.
- RC bellows.
- ECG gating leads.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with the RC bellows (if required) and ECG gating leads attached. If breath-hold technique is not possible, respiratory gating or triggering is recommended to reduce the respiratory artefacts. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the fourth thoracic vertebra, or the nipples. The patient can be placed feet first into the magnet if the ECG trace is unsatisfactory to change the polarity of the patient relative to the main field of the magnet (see *Gating and respiratory compensation techniques* in Part 1).

Suggested protocol

A three-plane localizer is optimal as the heart and vascular structures of the chest lie obliquely within the cavity of the chest. The images provided in three orthogonal planes provide a localizer so that oblique views of the heart and great vessels can be prescribed.

Coronal breath-hold fast incoherent (spoiled) GRE/SE T1 (Figure 10.10)

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Medium slices/gap are prescribed relative to the vertical alignment light, from the posterior chest muscles to the sternum. The area from the top of the sternum to the diaphragm is included in the image.

P 60 mm to A 80 mm

10

Axial SE/FSE T1 (Figure 10.11)

As for the Coronal T1, except slice thickness/gap is altered to fit the ROI. Prescribe slices from the inferior border of the heart to the superior aspect of the arch of the aorta (Figure 10.10).

Specific cardiac views

Long Axis view (two chamber): From the axial T1 projection, using a slice through the left ventricle, align the slice slab parallel to the intra-ventricular septum and ensure the slab covers the whole of the left ventricle (Figures 10.12 and 10.13).

   Four chamber view: from the long axis view align through the apex of the left ventricle and the mitral valve. Ensure the slice slab covers the whole of the left ventricle. This plane can also be acquired from the short axis view (Figures 10.14 and 10.15).

   Short Axis view: from the long axis view align perpendicular to the long axis view imaging plane so that the alignment is parallel to the mitral
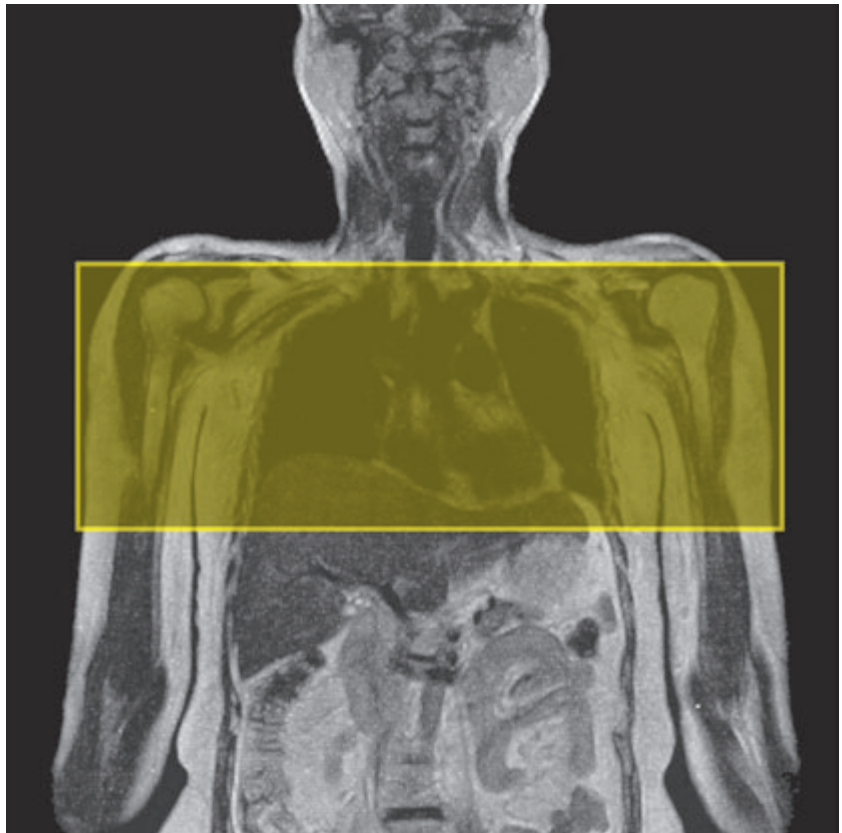
Figure 10.10 Coronal SE T1 weighted image through the chest cavity demonstrating slice prescription boundaries and orientation for axial imaging of the heart.
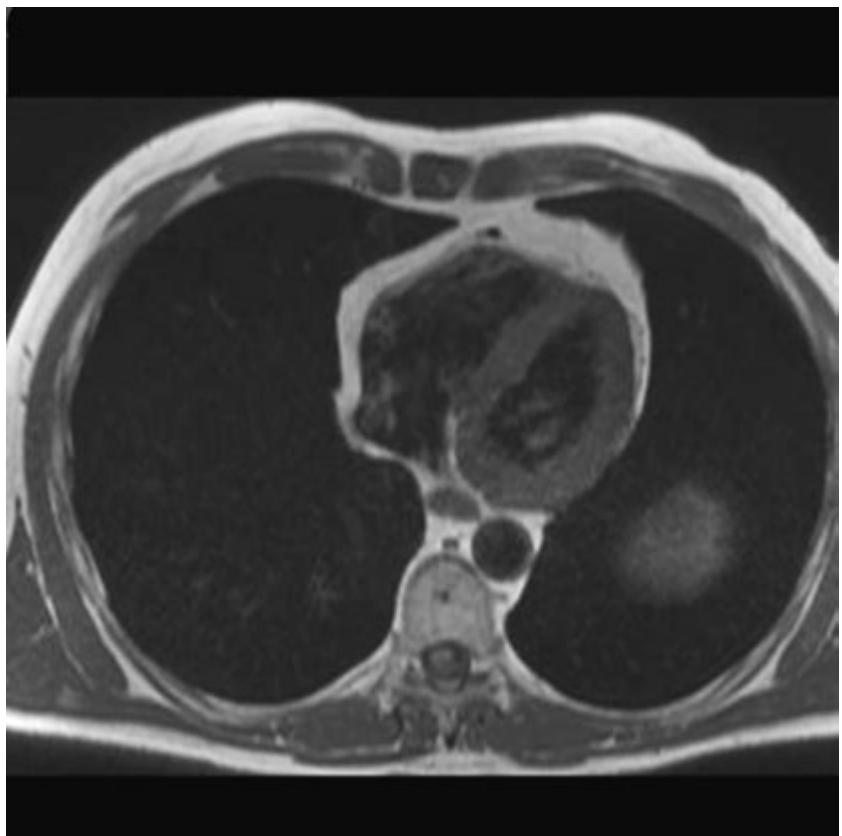
Figure 10.11 Axial T1 weighted FSE image of the chest using cardiac gating.
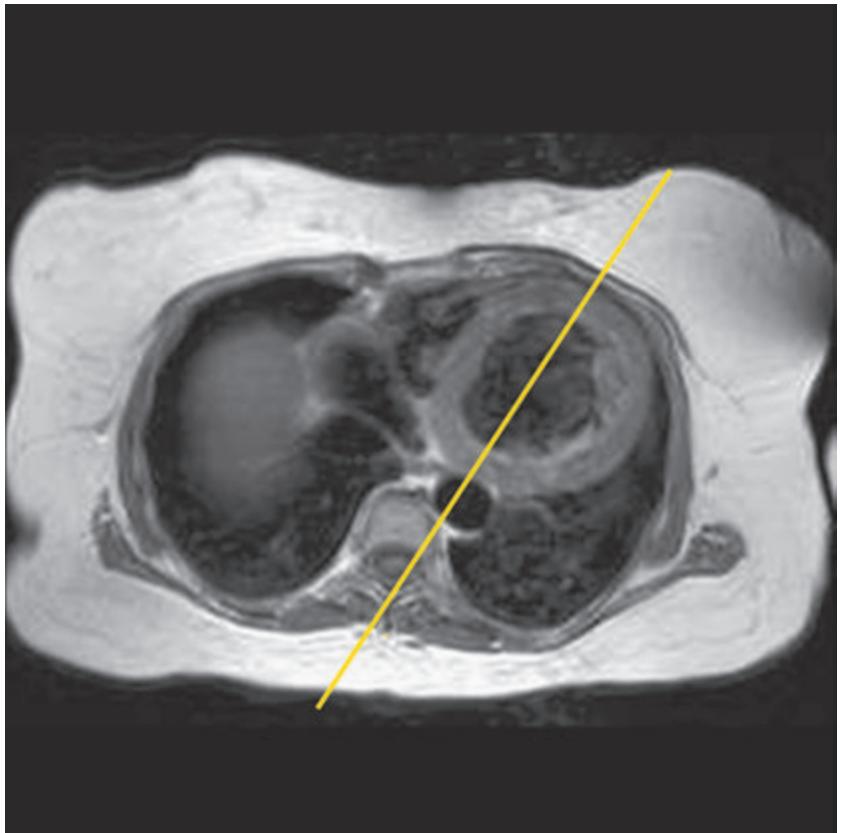
Figure 10.12 Axial FSE T1 weighted image showing slice orientation for the long axis view.
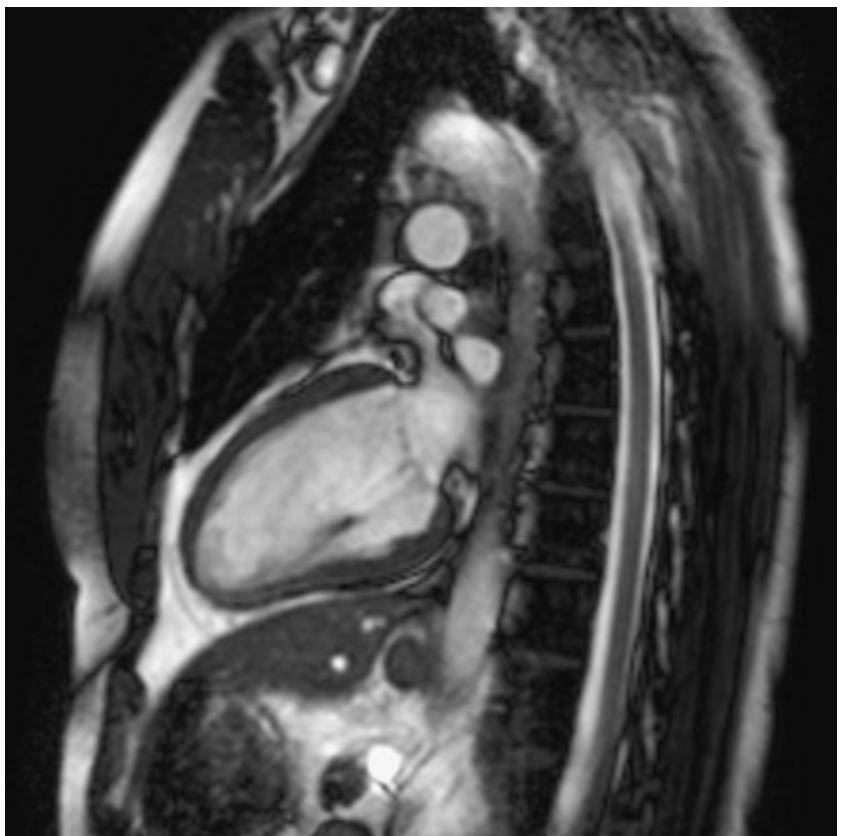
Figure 10.13 Two chamber long axis view.
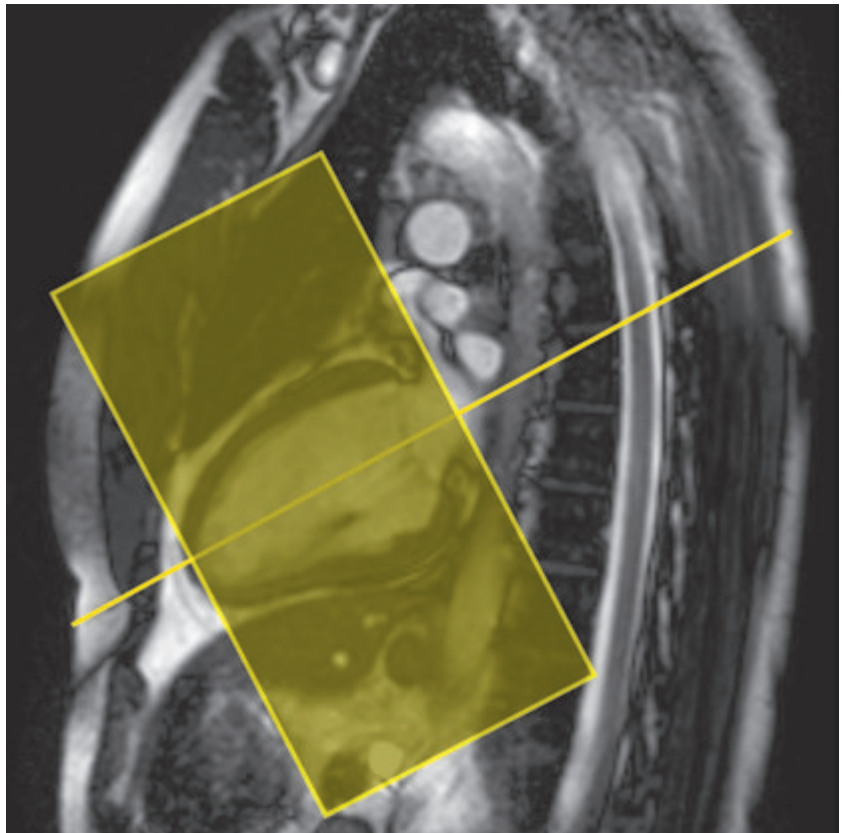
Figure 10.14 Long axis with slice orientation and slice boundaries for the four chamber view.
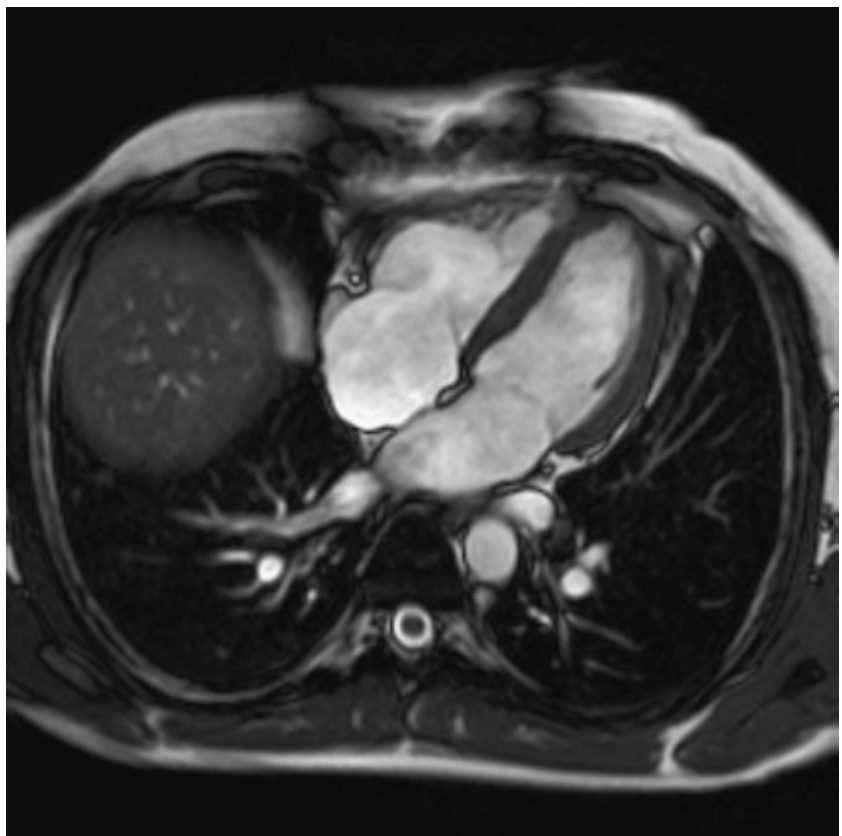
Figure 10.15 Four chamber view.
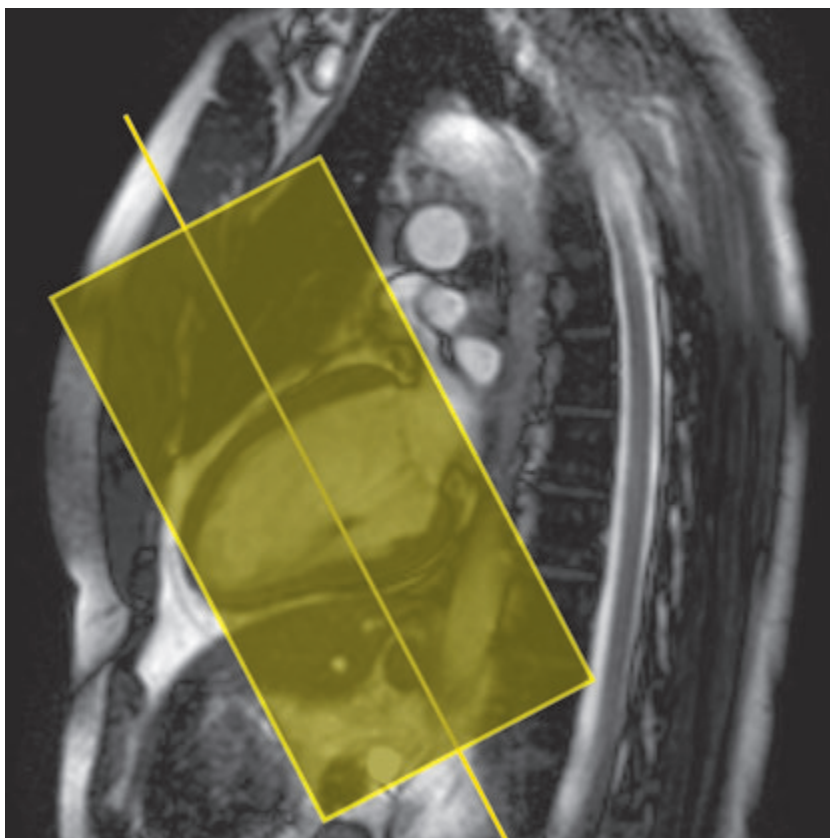
Figure 10.16 Long axis with slice orientation and slice boundaries for the short axis view.

valve. Ensure the slice slab covers the whole of the left ventricle (Figures 10.16 and 10.17). The short axis plane can also be prescribed from the coronal localizer. A location can be identified on the coronal localizer, posterior at the aortic root; and another on the coronal by paging the slices anteriorally to the apex of the heart. Once these locations are known, the short axis can be prescribed by explicitly identifying the locations. The scanner will essentially draw an imaginary line between the points and scan perpendicular to that imaginary line. The four chamber view can also be acquired from the short axis view by orientating the slice prescription through the left and right ventricles angled parallel to the diaphragm.

10

Sagittal/oblique SE T1

As for Axial SE T1, except slices are angled through the ascending and descending aorta and prescribed from one lateral edge of the vessel wall to the other.

This sequence is used to visualize the ascending and descending aorta in one view (candy cane or walking stick view). Select an image from the
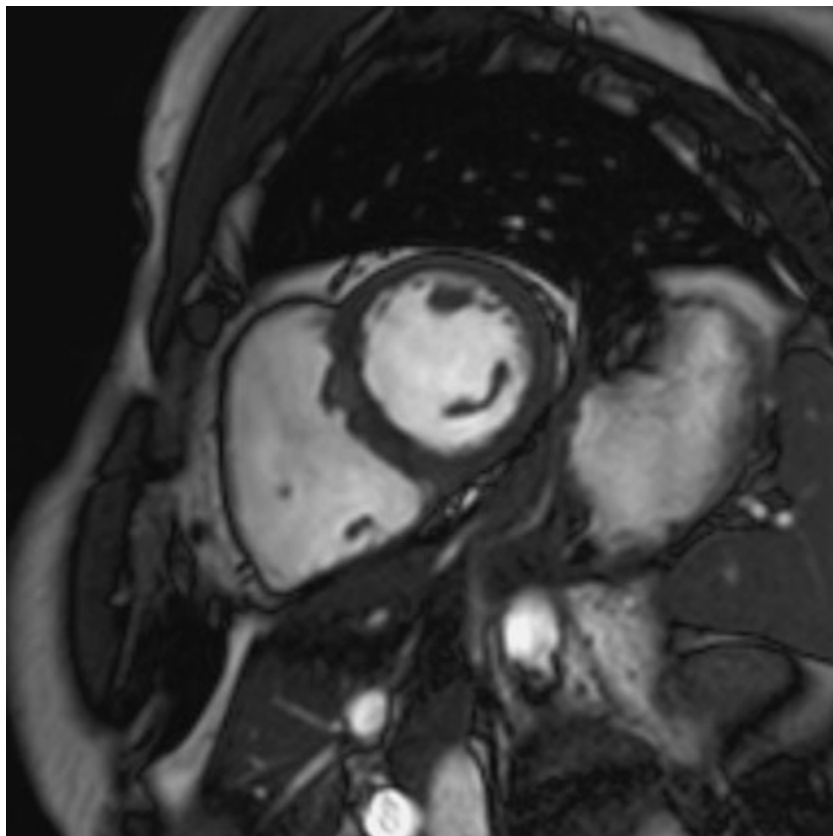
Figure 10.17   Short axis view.

10

axial series that demonstrates both portions of the aorta. Check slice position on a more superior slice that demonstrates the arch.

Black blood imaging vs bright blood imaging (Figure 10.18)

SE or FSE images are generally acquired with saturation pulses for the evaluation of black blood. Gradient echo, PC or EPI imaging sequences can be acquired with GMN for the evaluation of bright blood. Other black blood imaging techniques utilize a modified inversion recovery sequence, known as Double IR or Triple IR. Although the various vendors have unique acronyms for these sequences, the premise is the same. In each case the sequence begins with one 180° RF pulse followed by another 180° RF (double IR). In this case the sequence has essentially been driven to equilibrium. Since flowing blood does not stay within the slice for enough time to experience both 180° RF pulses, flowing blood appears black. In triple IR sequences, the double IR sequence has an additional 180° pulse at the frequency of fat for spectral presaturation. In this case, the suppression of epicardial fat combined with black flow within the cavity of the heart, allows for better visualization of the myocardium.
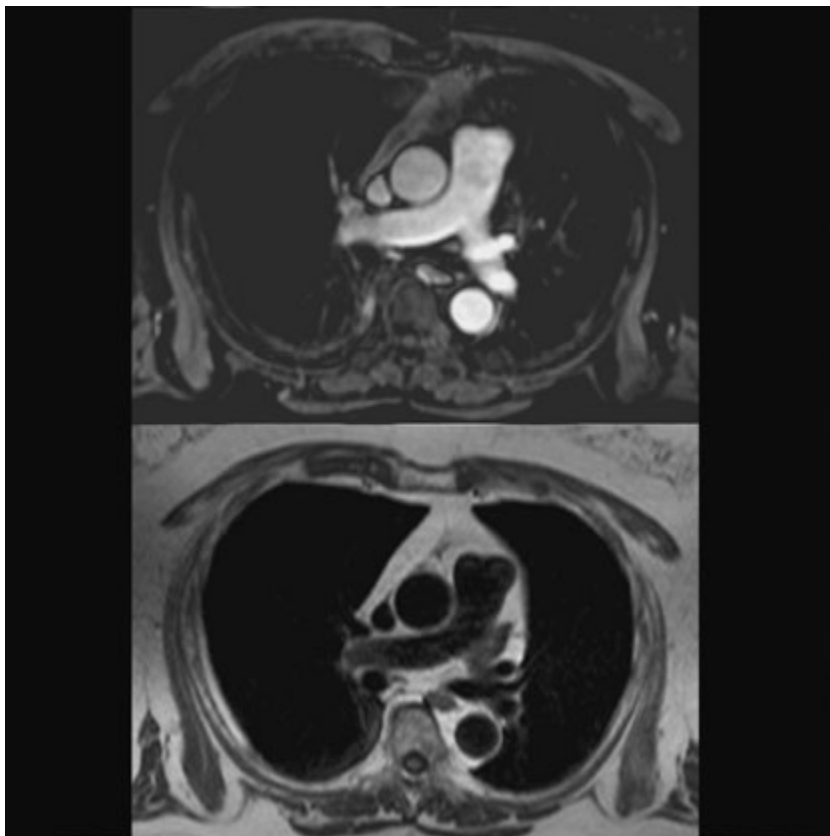
Figure 10.18 Axial images showing bright blood imaging (above) and black blood imaging (below) of the great vessels.

Oblique incoherent (spoiled) GRE T1 or coherent GRE T2* multiphase (cine)

Images of the heart, acquired during multiple phases of the cardiac cycle provide cardiac images during the beating of the heart. This technique is known as multiphase imaging. The more slices acquired within each cardiac cycle, the better the temporal resolution (resolution over time). For cardiac imaging temporal resolution, particularly in multiphase imaging, is limited by scan time. For example, if 16 phases of the cardiac cycle are to be acquired during one phase of the cardiac cycle this means that these images are acquired at the same slice location, but at different times during the cardiac cycle R–R interval.

Cardiac cine (like multiphase imaging) is used to assess cardiac function. The most common views for cardiac cine images are the short axis view or the straight axial view of the chest. This view is generally used to evaluate the left ventricle. For other areas of the heart, two chamber or four chamber views may be utilized. Two chambers are best demonstrated on a sagittal/oblique view, four chambers in the coronal/oblique

plane. Additional views such as the left ventricular outflow technique may also be useful.

Medium slices/gap are prescribed in the plane relevant to the ROI (often axial or oblique). Select the cine functions as appropriate to the system, i.e. number of slices and phases per acquisition (see *Gating and respiratory compensation techniques* in Part 1).

Additional sequences

SPAMM tagging

SPAMM (spatial modulation of magnetization) essentially modulates or varies the magnetic field in the region of the heart, like waves. Since the RF pulse is dependent upon the magnetic field, RF excitation pulses only excite tissues with the same frequency. Therefore the RF pulses match for example the peaks of the waves but not the valleys. The effect is a signal in the location of the RF match (resonance) and no signal in the areas where the RF pulse does not match the frequency. Modulation can be applied along several directions. If one direction is used stripes appear across the images. If modulation is applied along two perpendicular axes, then the resultant image has a grid-like appearance. The choice between stripes and grids is generally at the discretion of the radiologist.

This technique is used in conjunction with multiphase or fast cardiac SE or GRE sequences to assess myocardial wall function post-myocardial infarction. The SPAMM technique used with multiphase imaging enables visualization of the SPAMM stripes or grid that appear to move with the myocardium. In fact the stripes or grids not only move, but tend to fade away over time, during the cardiac motion in normal myocardium (or heart wall muscle). However in areas of myocardial infarction, the heart wall muscle does not move normally. SPAMM images therefore yield stripes or grids that persist rather than fade. This provides information about heart function.

SPAMM sequences, used in conjunction with cine PC, show promise for real-time imaging of the heart. In addition, PC images can be reconstructed as magnitude images or phase images. Magnitude images are reconstructed like MR images, where phase data are utilized to produce phase images. Phase images provide directional information about heart wall motion and flow direction.

EPI

This sequence, used in conjunction with cine PC, shows promise for real-time imaging of the heart and coronary vessels. In addition, EPI imaging is acquired with rapid imaging times for the reduction in motion artefacts. However EPI is plagued with image artefacts such as chemical shift, and susceptibility.
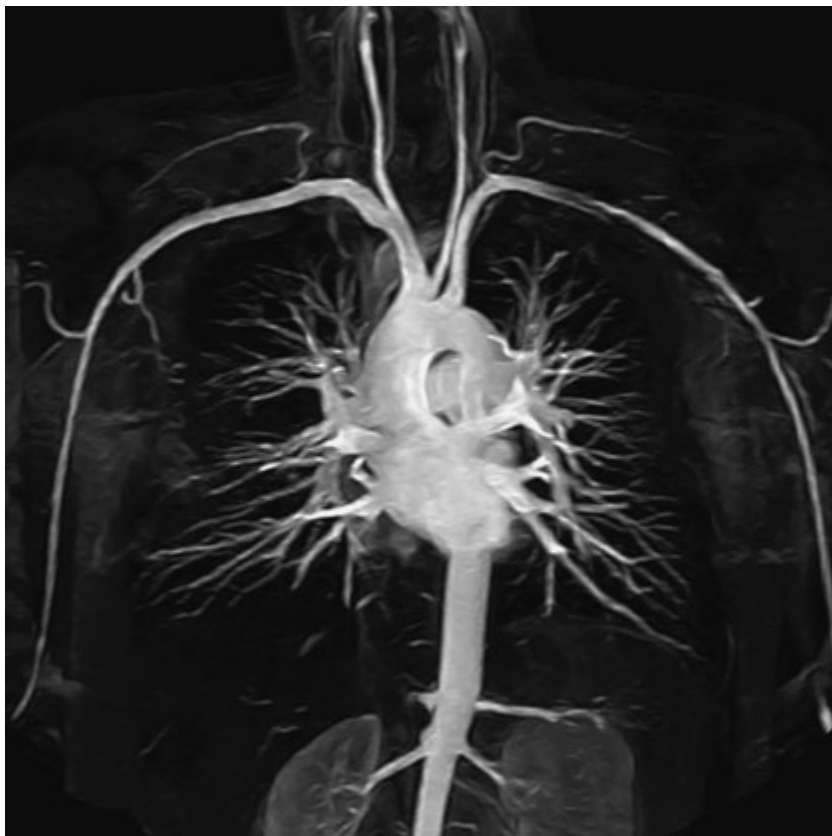
Figure 10.19   Coronal fast incoherent (spoiled) GRE T1 weighted image acquired after contrast enhancement.

10

Contrast enhanced cardiac and vascular studies (Figure 10.19)

Gadolinium enhanced GRE sequences of the heart can be used to demonstrate masses or infarcts of the heart as well as vasculature of the chest and heart. GRE with contrast enhancement, provide images with high signal in areas of flowing blood. MRA sequences, acquired with a sagittal oblique or the 'candy cane shot' of the aortic arch, can demonstrate comparison views of the aortic dissection.

Typically for the evaluation of the aortic arch, sagittal or sagittal oblique sequences are acquired. However, for the evaluation of the pulmonary arteries, the coronal plane is optimal. Pulmonary MRA sequences are acquired with dynamic contrast enhancement. For coronary artery imaging, high resolution, multiple oblique images with dynamic contrast enhancement are required for bright blood imaging (Figure 10.20).

Cardiac perfusion studies

In some cases, cardiac perfusion studies are used with, and without, pharmacologic (stress inducing) agents for the evaluation of cardiac function.
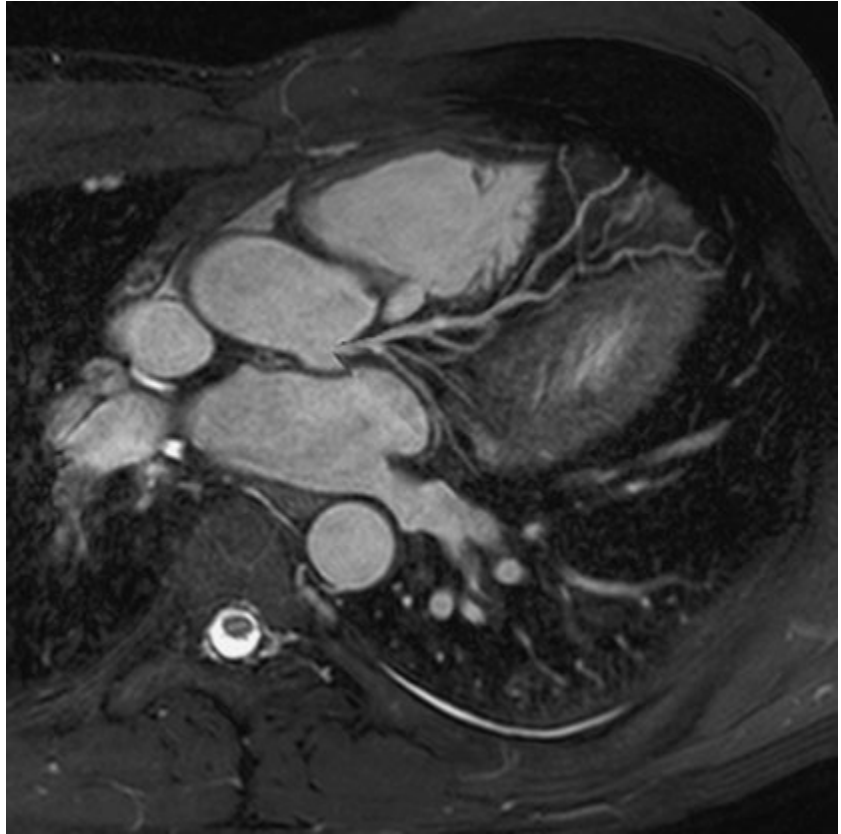
Figure 10.20   Coronary artery imaging after contrast enhancement.

10

One such agent is known as Dobutamine™. This agent produces cardiac stress and therefore imaging can be acquired during pharmaco-logically induced stress and while the heart is at rest. Such agents how-ever, may not be approved for use in MRI. For this reason caution should be taken in performing MR cardiac imaging during pharmacologically induced stress.

Diffusion imaging

Recent studies using diffusion tensor imaging to visualize the myocardium show some promise but require very strong and fast gradients.

Image optimization

Technical issues

As the chest has a relatively poor SNR, the implementation of a volume array coil helps maintain SNR. This is especially useful because thinner slices and a finer matrix are required for high-resolution imaging of

the heart. Remember however that the FOV is limited to the size of the coil. For smaller structures such as the heart and coronary arteries, multi-channel coils or phased array coils for improved SNR are recommended as they permit smaller voxels and therefore higher resolution. The use of multiple NEX/NSA not only reduces some respiratory and cardiac artefact, but also improves the SNR. The disadvantage of this strategy is the associated increase in scan time. This can be compensated for, to some degree, by the implementation of a coarser matrix.

Artefact problems

Respiratory, cardiac and flow motion are the most obvious artefacts in the chest. They occur along the phase encoding axis, and the degree to which they interfere with the image is mostly due to the proficiency of RC and ECG gating. Ensure the RC bellows are properly connected and are working efficiently. Alternatively, breath-hold techniques may be used to suspend respiration. Check that the ECG leads are correctly attached and that the ECG trace has good amplitude and is triggering correctly (see *Gating and respiratory compensation techniques* in Part 1) (Figure 10.21).
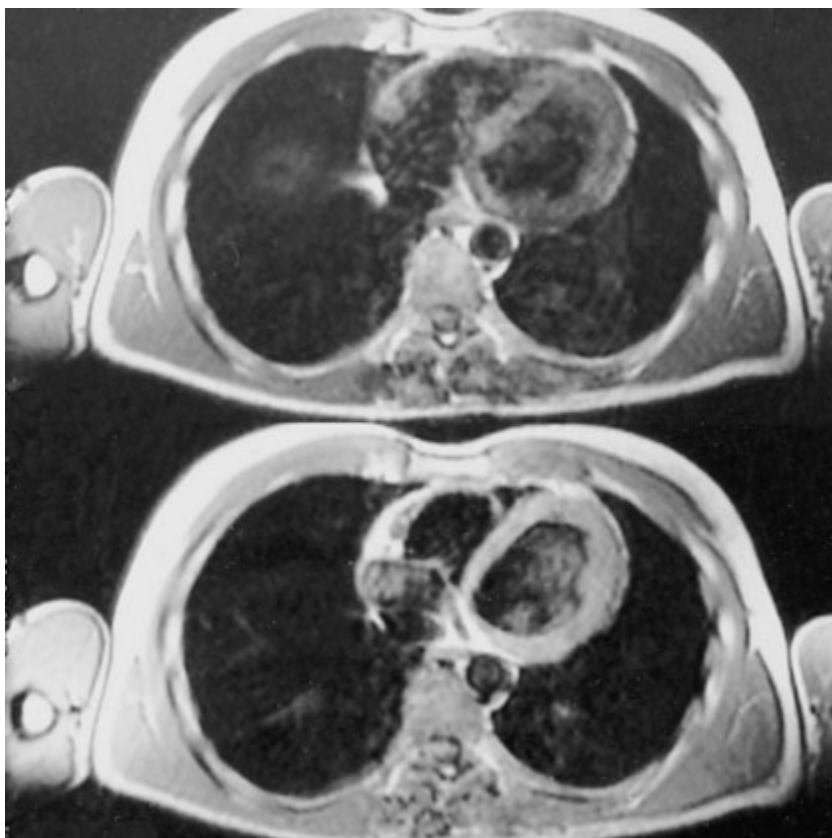
Figure 10.21 Axial images through the heart without cardiac gating (above) and with cardiac gating (below).

10

Spatial presaturation pulses are also important to further decrease flow artefact. They are placed S and I to the FOV to reduce flow artefact from the aorta and IVC. R and L presaturation pulses are beneficial in coronal images to decrease artefact from venous flow entering the chest from the subclavian vessels. When used in conjunction with SE sequences, spatial presaturation pulses produce black blood. If signal is seen within a vessel its may indicate either slow flow or occlusion. GMN reduces flow artefact further and is mainly used in cine imaging (see *Gating and respiratory compensation techniques* in Part 1). It is not commonly utilized in T1 weighted SE sequences as it increases signal in vessels and the minimum TE available. When used in conjunction with coherent GRE sequences, GMN produces bright blood. If a signal void is seen within a vessel, it may indicate either slow flow or occlusion.

Patient considerations

Patients who undergo MRI of the heart generally have cardiac problems. These patients should be closely monitored for cardiac function with pulse oximetry.

Also the cardiac gating leads, and hence the ECG tracing that is detected from these leads, may have been altered by the manufacturer to reduce the effect of the elevated 'T' wave caused by the magnetic field. This effect is known as the magnet–haemodynamic effect or the magnet–hydrodynamic effect. If the patient has a slow heart rate or a poor cardiac output, the system cannot always trigger off every R wave, thereby lengthening the scan time considerably. Under these circumstances limiting the number of sequences is beneficial, and continuous reassurance of the patient may steady their heart rate and respiration. Oxygen can also be administered for patients who are, or who become, short of breath. Due to excessively loud gradient noise associated with some sequences, hearing protection in the form of head phones or ear plugs is recommended to prevent hearing impairment.

Contrast usage

Contrast is routinely given for imaging the heart and great vessels in conjunction with fast GRE sequences and dynamic imaging of the heart, aortic arch, great vessels, pulmonary arteries and coronary arteries (see Figures 10.19 and 10.20). Double or triple doses may improve vascular visualization. In addition, cardiac masses can be sometimes well visualized after contrast enhancement.

10

Thymus

Common indications

- Thymic evaluation of myasthenia gravis.
- Evaluation of thymic masses in general.
- Evaluation of the post-operative mediastinum.

Equipment

- Body coil/volume torso array coil.
- RC bellows.
- ECG gating leads.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with the RC bellows (if required) and ECG gating leads attached. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the sternum. The patient can be placed feet first into the magnet if the ECG trace is unsatisfactory (see *Gating and respiratory compensation techniques* in Part 1).

Suggested protocol

10

Sagittal breath-hold fast incoherent (spoiled) GRE/SE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Medium slices/gap are prescribed on either side of the longitudinal alignment light. The area from the diaphragm to the apex of the lung is included in the image.

L 15 mm to R 15 mm

Axial SE T1

Medium slices/gap are prescribed through the thymus

Axial SE T1 + contrast

As for Axial SE T1, **except** use chemical/spectral presaturation to distinguish enhancing pathology from fat.

Additional sequences

Axial SE/FSE T2

Slice prescription as for Axial T1.

Image optimization

Technical issues

The chest has a relatively poor SNR as the proton density of the lung fields is low. In addition, there is little fat to give good contrast. The implementation of a volume array coil helps maintain SNR. This is especially useful when thinner slices and a finer matrix are required. The use of multiple NEX/NSA not only reduces some respiratory and cardiac artefact because of signal averaging, but also improves the SNR due to increased data collection. The disadvantage of this strategy is the associated increase in scan time, although this can be compensated for, to some degree, by the implementation of a coarser matrix. On some systems FSE is not compatible with RC techniques that use phase reordering. However, in conjunction with multiple NEX/NSA and a rectangular/asymmetric FOV, its implementation often increases both the resolution and SNR, and can be beneficial in examinations of the thymus.

Artefact problems

Respiratory, cardiac and flow motion are the most obvious artefacts in the chest. They occur along the phase encoding axis, and the degree to which they interfere with the image is mostly due to the proficiency of RC and ECG gating. Ensure the RC bellows are properly connected and are working efficiently. Alternatively, breath-hold techniques may be used to suspend respiration. Check that the ECG leads are correctly attached and that the ECG trace has good amplitude and is triggering correctly (see *Gating and respiratory compensation techniques* in Part 1). When implemented properly, ECG gating effectively reduces cardiac motion artefact. However, if ECG gating is inefficient, image quality is compromised.

The phase encoding axis usually lies A to P on axial images so that any phase ghosting interferes with the anteriorly situated thymus. It is therefore necessary to swap the phase axis to R to L to remove artefact from the thymus gland. This strategy positions the long axis of the anatomy along the phase axis, therefore oversampling is necessary to avoid aliasing, especially if the FOV is small (see *Flow phenomena artefacts* in Part 1).

Spatial presaturation pulses are also important to reduce flow artefact further. They are placed S and I to the FOV to decrease flow artefact from the aorta and IVC. GMN reduces flow artefact further but, as it also increases signal in vessels and the minimum TE available, it is not usually

10

beneficial in T1 weighted sequences. Additional shimming may be required before chemical/spectral presaturation sequences.

Patient considerations

Thymus imaging is generally acquired on paediatric patients as the thymus gland shrinks as the child matures. For this reason, sedation may be considered, depending upon the age of the child.

Patients are made as comfortable as possible and a careful explanation of the examination is important. If the patient is nervous, their ECG trace is often affected, thereby reducing the effectiveness of ECG gating. Under these circumstances continuous reassurance of the patient may steady their heart rate and respiration, and improve the efficiency of gating. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is often administered to improve the visualization of the thymus gland. This strategy is especially useful in conjunction with chemical/spectral presaturation pulses.

10

Breast

Basic anatomy (Figure 10.22)

10
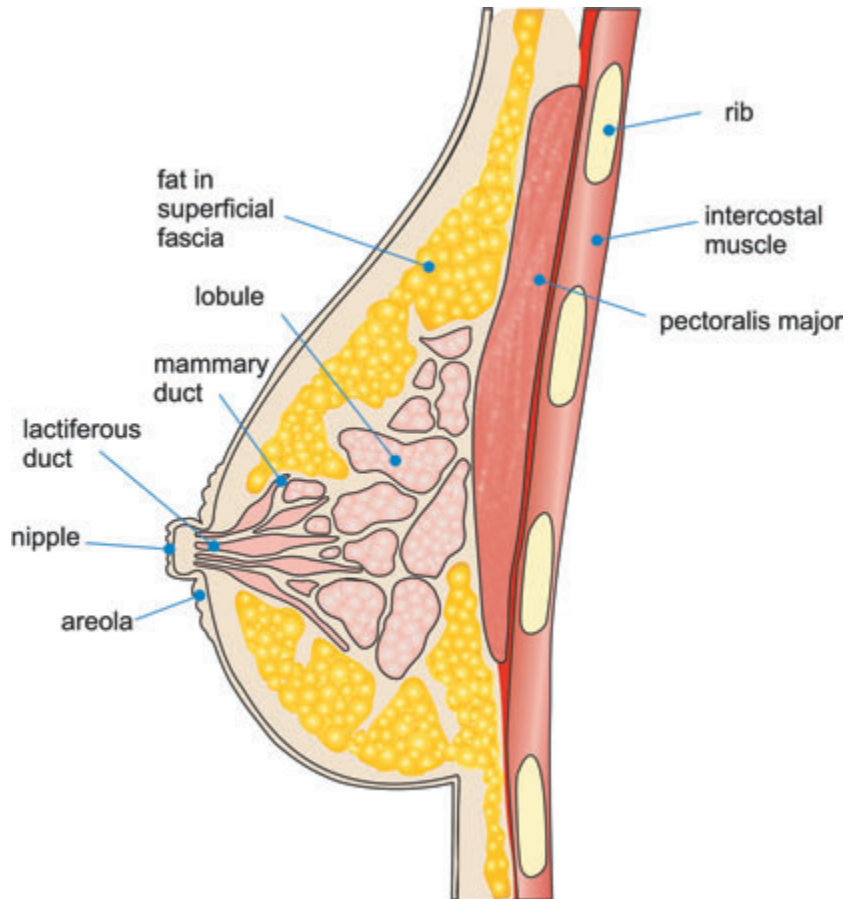
Figure 10.22 Sagittal section through the breast.

Common indications

For breast lesions

- Screening for high risk patients
- Staging of benign and malignant disease.
- Characterization of abnormalities in patients with breast implants.
- When conventional or digital is not optimal.
- Characterization of abnormalities in patients with very fatty or dense breasts.

For breast implants

- Implant rupture (linguine sign).
- Known rupture (intra-capsular vs. extra-capsular)
- Implanted patients with lesions

Equipment

- Breast coil(s) either single, double or phased array.
- Extension tubing, needle, contrast (MR-compatible biopsy needles if MR interventional procedure is planned).
- A magnetically safe automatic injector if available.
- Ear plugs.

Patient positioning

Patient positioning includes the patient lying prone, with breasts positioned within the breast coil. Exact patient position generally depends upon the method used for breast imaging. Some imaging centres choose to utilize the so called 'European Method', whereas others choose to do the so called 'US Method' (see later in *Technical considerations*). When evaluating lesions with the US method, images are acquired in the sagittal plane, one breast at a time. The European method acquires images in the axial plane imaging both breasts simultaneously.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the centre of the coil(s). For vertical field systems, breasts should be raised to isocentre in the anterior/posterior direction. This ensures that the breast is in the most homogeneous portion of the magnetic field, and therefore optimizes fat suppression on post-contrast images.

If contrast is given during the examination (for evaluation of breast lesions), a needle is inserted into the antecubital fossa prior to the examination. The contrast can then be administered through extension tubing so that patient movement is minimized during the injection. Alternatively, a magnetically safe automatic injector can be used if available. Power injectors are capable of delivering injections of consistent timing and dose. This becomes particularly useful for the evaluation of breast lesions when followed up. Furthermore, since the haemodynamics of the breast lesion is one determining factor for benign versus malignant lesions, consistent timing and dose of gadolinium contrast injection is important (see *Dynamic imaging* under *Pulse sequences* in Part 1).

A note on compression: Many breast lesions are associated with a large vascular supply that results in thick blood vessels known as neovascularity and angiogenesis. This neovascularity and angiogenesis result in high blood flow to the lesions known as hypervascularity. The hypervascularity of breast cancers causes rapidly enhancing lesions of the breast.

10

Overcompression of the breast may result in reduction in the visualization of some breast lesions. This occurs because the vascularity of some lesions is reduced upon compression and therefore will not enhance. Some coils have a compression device built into their design. When evaluating implants, and/or when using the European method, compression is not required. When using the US method the breast is reshaped (gently compressed) to reduce the number of slices required to cover the whole breast in a single acquisition. This provides dynamic images of the breast in acceptable imaging times. Some coils have a compression device built into their design.

Suggested protocol for the US method

Three-plane localizer/incoherent (spoiled) GRE T1

Three-plane localization is optimal for the evaluation of the breast in three orthogonal planes. For optimal breast imaging it is important to include all of the breast tissue from the superior axillary tail to the nipple, and posteriorly to include pectoralis muscle and chest wall.

Axial SE/FSE/incoherent (spoiled) GRE T1

If three-plane localization is unavailable, an axial localizer can be acquired. Thick slices/gap are prescribed through one or both breasts on either side of the horizontal alignment light.

I 25 mm to S 25 mm

Sagittal SE/FSE T1

High resolution images of the breast are acquired in the sagittal scan plane.
    Small FOV (sufficient to include the entire breast) are selected for high in-plane resolution. Thin slices/gap are prescribed through the breast(s) to include: medially from the sternum to laterally to include the axilla. Fat suppression should **not** be used on this acquisition, as lesions are generally dark relative to high signal intensity of fat within the breast.

Sagittal SE/FSE T2 +/− chemical/spectral presaturation

Slice prescription as for sagittal T1 acquisition for comparative slice locations and in-plane resolution. Fat suppression could be used on this acquisition, as lesions are generally bright relative to low signal intensity of suppressed fat within the breast.

Sagittal fast incoherent (spoiled) GRE T1+ chemical/spectral presaturation (pre-contrast)

Slice prescription as for sagittal T1 and T2 acquisitions for comparative slice locations and in-plane resolution. High resolution acquisitions provide

10
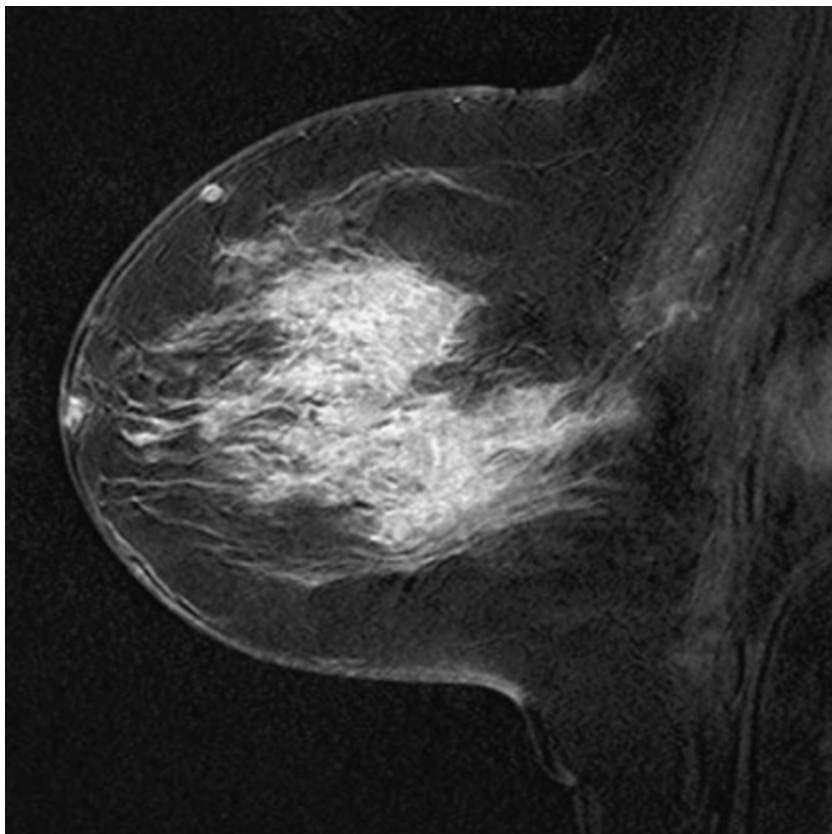
Figure 10.23 Sagittal incoherent (spoiled) GRE image post-contrast with chemical/spectral presaturation.

information about lesion architecture. In many cases, lesions that have speculated margins are likely to be malignant and lesions that have smooth edges are likely to be benign.

10

Sagittal 3D fast incoherent (spoiled) GRE T1+ chemical/spectral presaturation (post-contrast) (Figure 10.23)

Slice prescription as for sagittal T1 and T2 acquisitions for comparative slice locations and in-plane resolution. Images are acquired before and for several minutes after the injection. Scan times should not exceed $1^1/_2$ minutes per acquisition and should be repeated three to five times post injection. Timing the beginning of each acquisition after the commencement of the injection is necessary for image interpretation. Fat suppression is useful as enhancing lesions have a high signal relative to low signal intensity of suppressed fat within the breast.

Sagittal fast incoherent (spoiled) GRE T1 (post-processing)

Subtraction techniques remove additional signal from fat. In this technique the pre-contrast images are subtracted from the post-gadolinium images.

The resultant images demonstrate enhanced structures only. In addition, maximum intensity projection (MIP) processing permits evaluation of breast vasculature. Hypervascularity may indicate malignant disease of the breast. Breast workstations are increasing in popularity as they provide colourization and reformatting opportunities for further evaluation of breast lesions.

Suggested protocol for the European method

Three-plane localizer or axial localizer/incoherent (spoiled) GRE T1

The localizer for this method is the same as that for the US method described above. However if this is not available on the system, an axial localizer is adequate.

Axial SE/FSE/incoherent (spoiled) GRE T1

If three-plane localization is unavailable, an axial localizer can be acquired. Thick slices/gap are prescribed through one or both breasts on either side of the horizontal alignment light.

I 25 mm to S 25 mm

Axial SE/FSE T1 (Figure 10.24)

High resolution images of the breast are acquired in the axial scan plane. A FOV large enough to include both breasts is selected. Thin slices/gap are prescribed through the breast(s) to include: all of the breast tissue from the superior axillary tail to the nipple, and posteriorly to include pectoralis muscle and chest wall.

Fat suppression should not be used on this acquisition, as lesions are generally dark relative to high signal intensity of fat within the breast.

Axial SE/FSE T2 +/– chemical/spectral presaturation (Figure 10.25)

Slice prescription as for Axial T1 acquisition for comparative slice locations and in-plane resolution. Fat suppression could be used on this acquisition, as lesions are generally bright relative to low signal intensity of suppressed fat within the breast.

Axial 3D fast incoherent (spoiled) GRE T1 + chemical/spectral presaturation (pre-contrast) (Figure 10.26)

Slice prescription as for Axial T1 and T2 acquisitions for comparative slice locations and in-plane resolution. As for the US method but images are acquired in the axial plane.

10
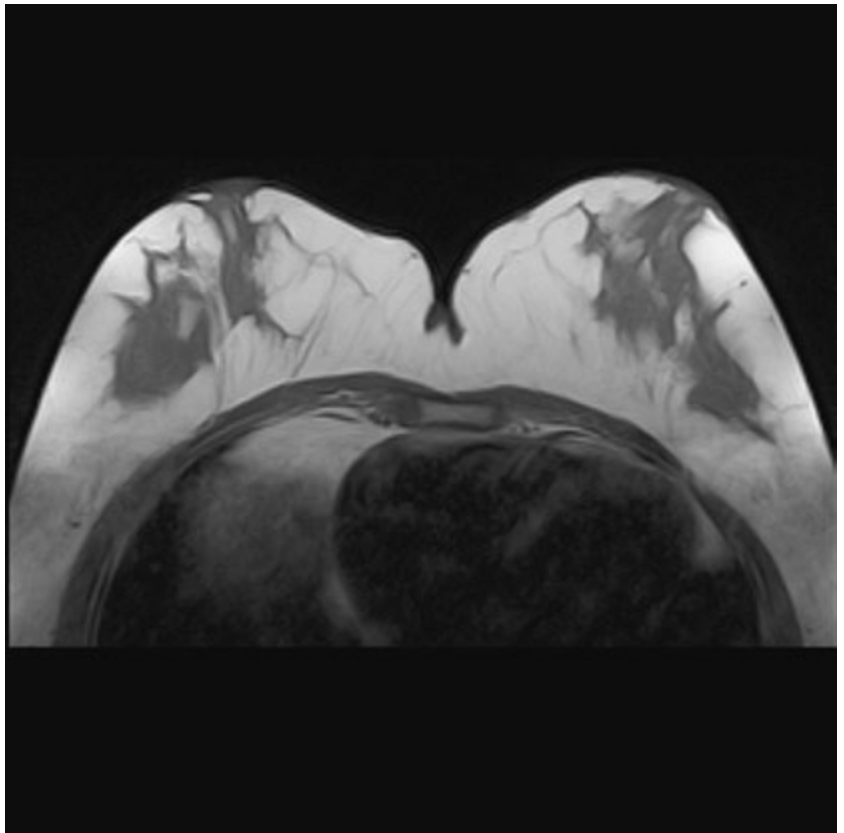
Figure 10.24 Axial SE T1 weighted image through both breasts**.**
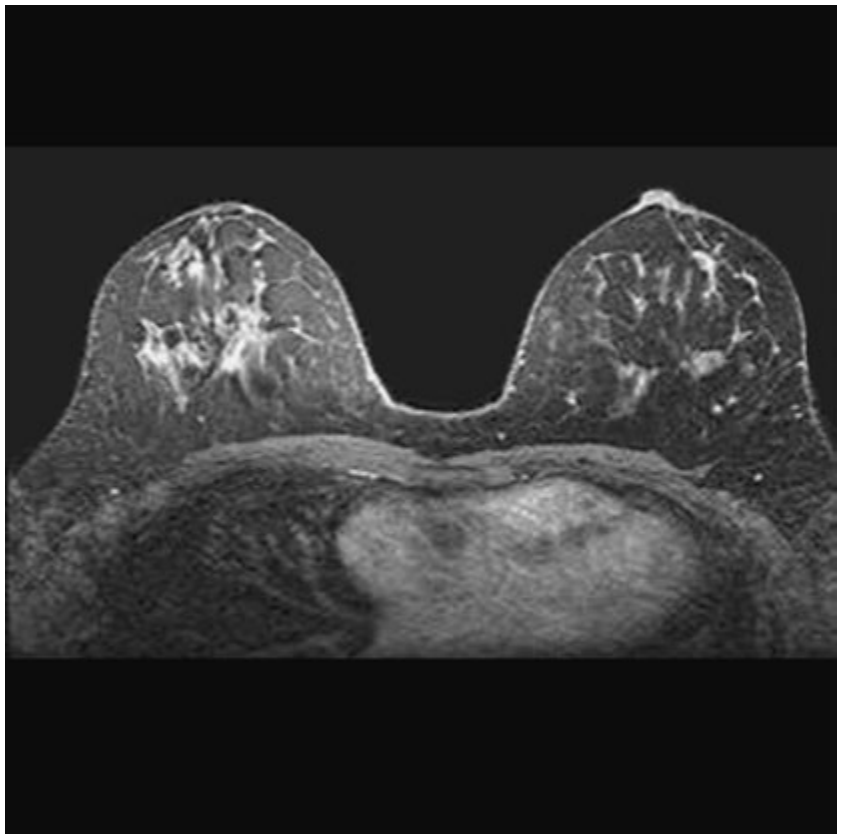
Figure 10.25 Axial T2 weighted image through both breasts.

Figure 10.26 Axial incoherent (spoiled) GRE image with chemical/spectral presaturation.

10

Axial 3D fast incoherent (spoiled) GRE T1 + chemical/spectral presaturation (post-contrast)

As for the US method but images acquired in the axial plane.

Suggested protocol for the evaluation of silicone implants

Three-plane localizer or axial localizer/incoherent (spoiled) GRE T1

As for US and European methods described above.

Sagittal T1 and T2 FSE (high resolution)

Slice location and resolution as that for the US method.

Sagittal spectral IR or IR-FSE + chemical/spectral presaturation + contrast

In order to evaluate implants, ruptured or intact, sequences that suppress either silicone or fat and water together are necessary. These suppression

techniques involve either the suppression of water (using water presaturation pulses) and fat within the breast using STIR to visualize silicone, (known as silicone imaging) or the suppression of silicone itself for the visualization of the other breast anatomy (known as silicone suppression). The choice between silicone imaging or silicone suppression is generally the responsibility of the radiologist.

Slice prescription as for Sagittal T1 in the US method or axial prescriptions in the European method.

Additional sequences

Axial SE/FSE T1/T2 or STIR

Useful to visualize implants. Chemical/spectral presaturation can be implemented in conjunction with SE/FSE sequences instead of STIR. Note: STIR should not be used after contrast enhancement (*see Pulse sequences* in Part 1).

STIR with water suppression produces images that show only silicone.

SS-FSE/SE-EPI/GRE-EPI/diffusion imaging

The use of real-time imaging has applications in the breast. These include biopsies and thermal or focused RF ablations of lesions under real-time MR control. DWI of the breast may have potential uses in the differentiation of benign from malignant lesions and it may enable evaluation of the response of metastases to chemotherapy.

Image optimization

10

Technical issues

Developments in coil technology have greatly increased the SNR characteristics of breast coils. Phased array coils return the highest and most uniform signal, whereas some others can give glare at the nipple, and signal fall-off nearer the chest. There is usually good tissue contrast and, as the SNR is relatively high, spatial resolution can be maximized. FSE is a great advantage in breast examinations as it facilitates the acquisition of very fine matrices in relatively short scan times. Parallel imaging can also be a useful tool for reducing scan time, without reducing resolution. Multi-channel coils are required.

Some imaging centres chose to utilize the so called 'European method', whereas others choose to use the so called 'US Method'. Each method includes high resolution images acquired with a rapid scan time, during dynamic contrast enhancement.

The **European method** acquires the breast images using an axial scan plane. In this method axial images are acquired to include both breasts on

the same axial image. This requires a FOV that is relatively large and, although high imaging matrices are generally selected to provide improved in-plane resolution, this lengthens the scan time, which is not optimal for dynamic imaging. Thin slices may be used depending upon the coverage required and through-plane resolution desired but coverage may be a problem.

The **US method** acquires images in the sagittal scan plane, one breast at a time, either unilaterally or bilaterally. As this plane covers the breast in fewer slices, acquisition times are shorter (ideal for dynamic imaging). In addition as a smaller FOV is required very high in-plane and through-plane resolution is achieved. Unilateral breast imaging opts to image the breast in question then, on another date, the contra-lateral side (because another dose of gadolinium to image the contra-lateral side cannot be given on the same day). Bilateral acquisition can be achieved however by imaging one breast then the other within the same acquisition. A more optimal bilateral acquisition produces 3D scans, acquired with inter-leaved acquisition, dynamically during contrast enhancement.

The caveat for the US method is that the breast images are generally acquired one breast at a time, whereas the European method acquires both images simultaneously.

The caveat for the European method is that many facilities, in an attempt to see more anatomy (of the chest and surrounding structures), tend to use less than optimal in-plane resolution (large FOV and/or low matrix) compared with the US method, which uses high in-plane resolution (small FOV and/or high matrix) sagittal images.

Chemical/spectral presaturation pulses and other fat suppression techniques are useful in breast imaging to distinguish a lesion from the surrounding fatty breast tissue. Conventional fat suppression is not always optimal, particularly on axial bilateral European acquisitions that use a large FOV, resulting in shading on breast images. Unfortunately, STIR (albeit a homogenous fat suppression technique) cannot be used after gadolinium as it suppresses gadolinium enhancing lesions. Spectral suppression techniques, which improve the homogeneity of fat suppression, often produce more uniform suppression across a large FOV.

Local magnetic field homogeneity can also improve the quality of fat suppression with these techniques. For this reason, shimming may be required before chemical/spectral presaturation sequences. Shimming for the breast can be troublesome however. Breasts can be shimmed unilaterally or bilaterally. Bilateral shim generally includes both breasts, the air between the breasts and the anterior chest wall and therefore a number of different tissue types. With a unilateral shim, the suppression is more optimal, as the shim volume includes tissues of similar composition. However, the contra-lateral breast will have a sub-optimal shim (Figures 10.27 and 10.28).

Artefact problems

Respiratory artefact is somewhat reduced by laying the patient prone rather than supine. Also the coil(s) do not move during respiration when

Figure 10.27 Sagittal image of the breast after bad shimming.

10
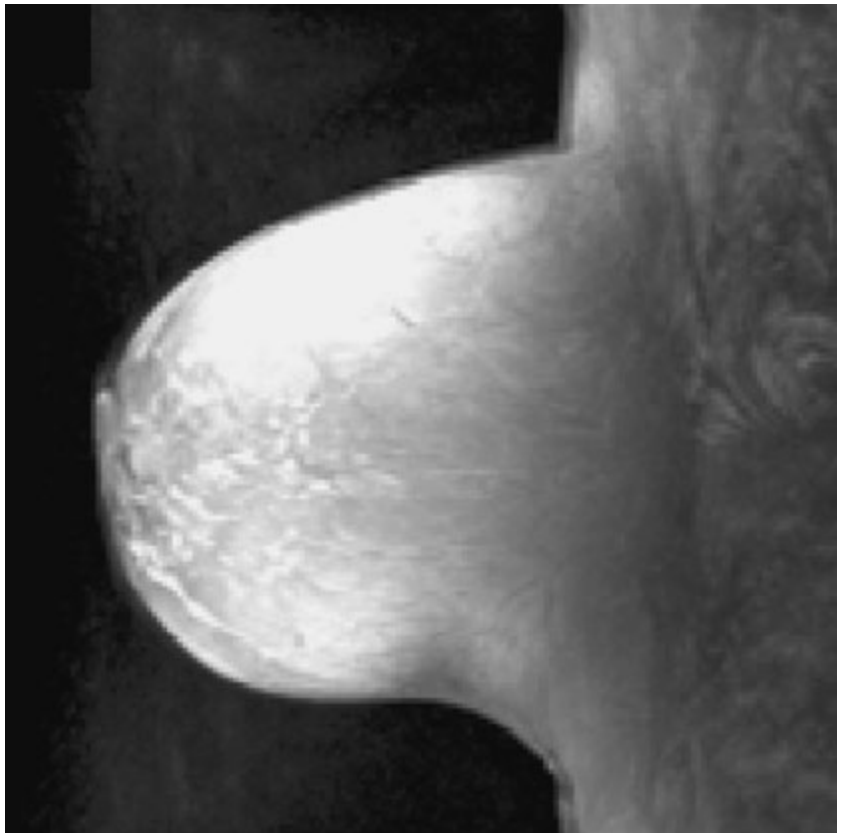
Figure 10.28 Sagittal image of the breast after good shimming.
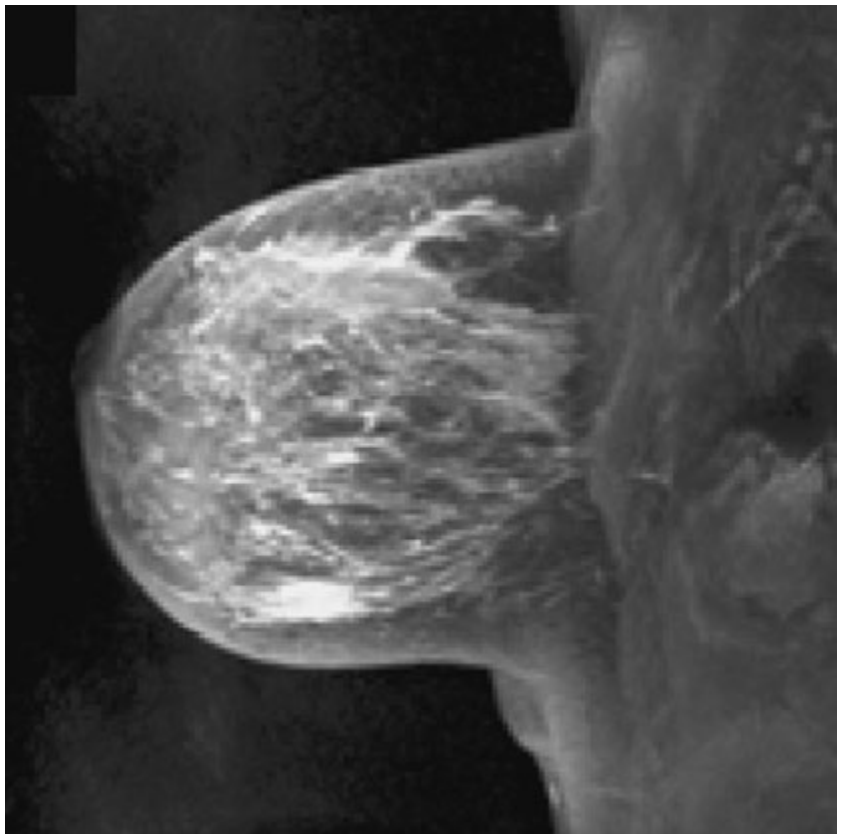
the patient is prone. Cardiac motion and flow within the mammillary vessels can also be troublesome. Swapping the phase encoding axis to S to I on sagittal images and R to L on axials moves the artefact posterior to the breast, but it can then interfere with the axilla. Therefore, repeat scans with the phase axis returned to its original direction are usually required if the axillae are also under investigation. Oversampling is necessary when the phase axis is swapped if signal is returned by tissue that lies within the coil, but outside the FOV in the phase direction. Spatial presaturation pulses brought into the FOV and placed posteriorly over the heart are useful in reducing cardiac motion artefact.

Patient considerations

Many patients are very anxious, as some have already had an abnormal mammogram and/or previous disease. Reassurance and a careful explanation of the procedure are therefore more important than usual. The rather complicated and time-consuming nature of this examination can be daunting to the patient. It is vital that she does not move during or after the injection, because the dynamic sequence is planned from the previous axials and comparisons are made between the pre- and post-contrast images.

As the patient has to lie in a rather unnatural position (prone with arms back or forward), and the examination is fairly lengthy, it is important to ensure that the patient is comfortable before the examination begins. Some studies show that, due to hormonally influenced tissue changes in the breast, this examination should be performed 10–15 days into the menstrual cycle. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

10

Contrast usage

Contrast is used in conjunction with rapid imaging to evaluate the temporal resolution of a lesion (see *Dynamic imaging* under *Pulse sequences* in Part 1). This dynamic acquisition allows for the evaluation of the haemodynamics of the breast lesion. In many cases, lesions that wash in and out quickly are likely to be malignant. Lesions that wash in/out slowly are likely to be benign.

The optimal imaging window for the evaluation of breast cancer is approximately 10 days post menses. At other times during the menstrual cycle there can be hormonal variability and normal breast parenchyma can enhance, obscuring small lesions. Unfortunately, patients are generally anxious to have the investigation as soon as possible rather than waiting for time to evolve between their menstrual cycle. If this is the case and the patient cannot wait, care should be taken to make the radiologist aware of this as unexplained enhancement may occur in normal breast tissue. This is somewhat inefficient, however, as these patients may need to have their examination repeated at the correct time during their menstrual

cycle. Repeated examinations should wait at least 24 hours to allow gadolinium to be excreted.

Unilateral breast imaging opts to image the breast in question then, on another date, the contra-lateral side. For unilateral imaging, the breast in question should be imaged dynamically. A look at the post-contrast image of the contra-lateral side is **not** recommended as many breast lesions wash out before the delayed image is acquired and may produce false results. Remember, repeat examinations should wait at least 24 hours to allow gadolinium to be excreted.

Bilateral scans image one breast then the other within the same acquisition. An optimal bilateral acquisition produces interleaved 3D scans dynamically during contrast enhancement. In this example, a 3D acquisition would acquire, nearly simultaneously, the right breast, then the left breast, and then the right again etc. during the injection and for several minutes post injection.

10

Axilla

Common indications

- Diagnosis and characterization of metastatic disease of the axillary lymph nodes especially, but not exclusively, in patients with carcinoma of the breast.
- Diagnosis and characterization of axillary masses.

Equipment

- Body coil/surface coils/phased array/multi array coils.
- RC bellows.
- Pe gating leads.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with their arms at rest by their sides, or over their heads, with the coil placed over the axilla. The RC bellows (if required) and Pe gating leads are securely attached. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the axillae. Both axillae can be examined together.

Suggested protocol

Coronal SE/FSE/breath-hold fast incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gap are prescribed relative to the vertical alignment light, from the posterior chest muscles to the sternum. Both axillae and supraclavicular areas are included in the image.

P 60 mm to A 80 mm

Axial SE/FSE T1

Medium slices/gap are prescribed through both axillae and supraclavicular fossae.

Axial SE/FSE PD/T2 or STIR

Slice prescription as for Axial T1, **except** use chemical/spectral presaturation on SE/FSE sequences.

Additional sequences

Sagittal SE/FSE T1 and T2

Provides an additional plane to visualize the brachial plexus. Prescribe slices from the sternoclavicular joint medially to the humerus laterally.

Image optimization

Technical issues

There is usually relatively good inherent SNR and contrast in the axilla. This can be further improved if surface coils are placed near the axillae, or phased array breast coils are used instead of the body coil. Good resolution is obtained by using medium to fine matrices, the smallest FOV possible and medium slices, without jeopardizing the SNR. SE sequences are traditionally used to demonstrate anatomy and pathology, but FSE is also beneficial despite some respiratory and flow motion. This is especially true on T2 images as the associated scan time reduction enables the implementation of finer matrices, and therefore greater resolution is obtained. Image quality is further optimized by the selection of multiple NEX/NSA, which effectively reduces flow and respiratory motion artefact due to increased signal averaging. In axial imaging, a rectangular/asymmetric FOV is beneficial (especially in conjunction with FSE) with the long axis of the rectangle placed R to L. However, if a particularly small FOV is selected aliasing may be a problem. Spatial presaturation pulses placed A and P to the FOV are required to reduce this (see *Flow phenomena and artefacts* in Part 1).

Artefact problems

The main source of artefact in this area is from respiratory and flow motion in the subclavian vessels. Using FSE in conjunction with multiple NEX/NSA is often just as effective at reducing respiratory artefact as RC in this area. Phase ghosting occurs along the A to P axis on the axial images, so it does not usually interfere with the axillae. However, on the coronal series, phase artefact in the R to L axis can be troublesome. R and L spatial presaturation pulses brought into the FOV reduce flow artefact entering the axillae from the subclavian veins, but care must be taken to ensure that they do not saturate important anatomy. GMN is also useful to reduce artefact further but, as it gives vessels a high signal and increases the minimum TE, it is not usually beneficial in T1 weighted sequences.

Additional shimming may be required before chemical/spectral presaturation sequences.

Patient considerations

The patient's arms are placed either at the sides or over the head, and secured with immobilization pads if required. Inform the patient of the

10

importance of keeping the arms still during the examination. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast can be given to identify pathology in this area. As the axillae sometimes contain fat, fat suppression techniques are often necessary. This is especially true on FSE T2 weighted images where fat returns a signal similar to pathology.

10

Brachial plexus

Basic anatomy (Figure 10.29)
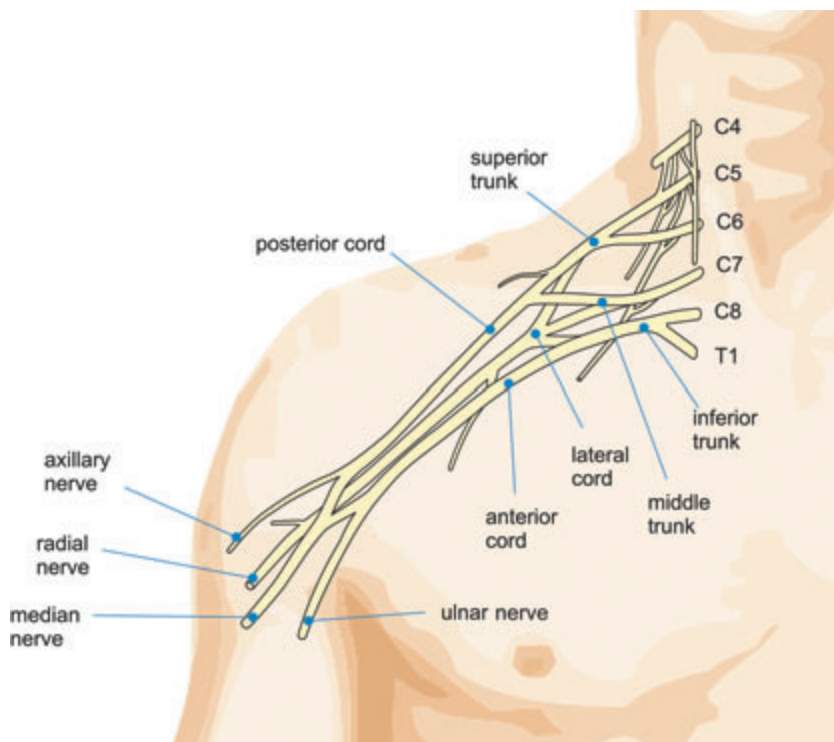
Figure 10.29 The components of the brachial plexus.

Common indications

- Diagnosis and characterization of brachial plexus lesions, especially those secondary to carcinoma of the breast and the bronchus.
- Thoracic outlet syndrome.
- Evaluation of the brachial plexus following trauma.

Equipment

- Body coil/anterior neck coil/volume neck coil/multi-array coils.
- RC bellows.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch and the RC bellows are attached if required. The patient is positioned so that the longitudinal

alignment light lies in the midline, and the horizontal alignment light passes through the level of the sternoclavicular joints.

Suggested protocol

Axial SE/FSE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gap are prescribed on either side of the horizontal alignment light. The area from the sternoclavicular joints to the third cervical vertebra is included in the image.

I 25 mm to S 25 mm

Coronal SE/FSE T1 (Figure 10.30)

Thin slices interleaved are prescribed from the posterior aspect of the cervical cord to the sternoclavicular joints. The area from the third cervical vertebra to the aortic arch is included in the image.

Axial 3D incoherent (spoiled) GRE T1

Thin slices and a small or medium number of slice locations are prescribed from the arch of the aorta to the third cervical vertebra. Coverage may be extended to allow for slice wrap.

Axial SE/FSE PD/T2

Thin slices/gap are prescribed from the arch of the aorta to the third cervical vertebra. Chemical/spectral presaturation pulses are sometimes useful to differentiate tumour from fat.

Image optimization

Technical issues

The SNR and CNR characteristics of the brachial plexus are dependent on the type of coil used. Surface coils and specifically designed volume coils return a higher signal than the body coil, and therefore improved spatial resolution is obtained. SE provides optimum contrast, but FSE can be implemented if required. Spatial resolution is important as it is necessary to demonstrate the nerve pathways within the brachial plexus. The coronal series requires the thinnest slices possible with interleaving. A volume acquisition is also beneficial as very thin slices with no gap are acquired, along with visualization of anatomy in any plane. However, the scan times are quite lengthy, increasing the likelihood of patient

10
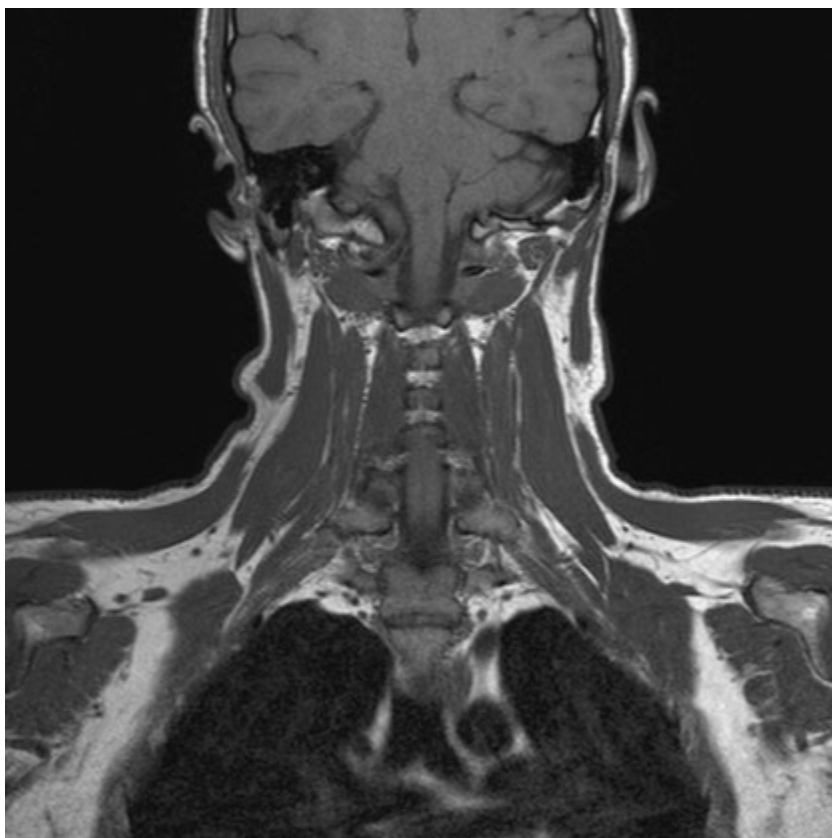
Figure 10.30   Coronal SE T1 weighted image of a normal brachial plexus.

movement. As the purpose of the volume acquisition is to demonstrate anatomy, an incoherent (spoiled) GRE T1 is the pulse sequence of choice.

10

Artefact problems

The main source of artefact is from respiratory motion, and therefore RC is used if this is especially troublesome. Alternatively breath-hold techniques may be utilized to suspend respiratory motion. Motion artefact occurs in the phase direction, and therefore swapping the phase axis to S and I on the coronal series is often beneficial. As a fairly small FOV is selected to optimize spatial resolution, aliasing is a problem if the body coil is used. Oversampling is therefore necessary if anatomy lies within the coil but outside the FOV in the phase direction.

Spatial presaturation pulses are important in the S to I direction to reduce flow in the carotid and jugular vessels. In addition, on the coronal series, R and L spatial presaturation pulses decrease flow artefact from the subclavian vessels. GMN also reduces flow artefact but, as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. There is always some slice wrap on the first and

last slices of the volume acquisition. Spatial presaturation pulses placed over anatomy outside the volume, in the direction of slice acquisition, significantly reduce this. For example, in an axial volume acquisition, spatial presaturation pulses placed S and I to the imaging volume nullify signal from slices that may wrap into the volume from above and below (see *Volume imaging* under *Parameters and trade-offs* in Part 1).

Patient considerations

Warn the patient of the length of the volume acquisition and the importance of keeping still. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be used to enhance masses in the brachial plexus but is not routinely given.

11

Abdomen

11

Table 11.1 Summary of parameters. The figures given are general and should be adjusted according to the system used (Table 2.1)

Spin echo (SE)

short TE	min to 30 ms
long TE	70 ms +
short TR	300−600 ms
long TR	2000 ms +

Fast spin echo (FSE)

short TE	min–20 ms
long TE	90 ms +
short TR	400−600 ms
long TR	4000 ms +
short ETL	2−6
long ETL	16 +

Inversion recovery (IR) T1

short TE	min–20 ms
long TR	3000 ms +
medium TI	200−600 ms
short ETL	2−6

STIR

long TE	60 ms +
long TR	3000 ms +
short TI	100−175 ms
long ETL	12–20

FLAIR

long TE	60 ms +
long TR	3000 ms +
long TI	1700−2200 ms
long ETL	12–20

Coherent GRE

long TE	15 ms +
short TR	≤ 50 ms
flip angle	20°−40°

Incoherent GRE

short TE	min–5 ms
short TR	≤ 50 ms
flip angle	20°−40°

Balanced GRE

TE	minimum
TR	minimum
flip angle	≥ 40°

SSFP

TE	minimum
TR	40−50 ms
flip angle	20°−40°

Slice thickness

2D	thin	2−4 mm
	medium	5−6 mm
	thick	8 mm
3D	thin	≤ 1 mm
	thick	≥ 3 mm

Slice numbers

Volumes	small	≤ 32
	medium	64
	large	≥ 128

Matrix (frequency × phase)

coarse	256 × 128 or 256 × 192
medium	256 × 256 or 512 × 256
fine	512 × 512
very fine	≥ 512 × 512

FOV

small	≤ 18 cm
medium	18−30 cm
large	≥ 30 cm

PC-MRA

2D and 3D	TE	minimum
	TR	25−33 ms
	flip angle	30°
VENC venous	20−40 cm/s	
VENC arterial	60 cm/s	

NEX/NSA

short	≤ 1
medium	2−3
multiple	≥ 4

TOF-MRA

2D	TE	minimum
	TR	28−45 ms
	flip angle	40°−60°
3D	TE	minimum
	TR	25−50 ms
	flip angle	20°−30°

11

Liver and biliary system

Basic anatomy (Figure 11.1)

Figure 11.1 The components of the liver and biliary system.

Common indications

- Focal lesions and staging of neoplasms.
- Benign hepatic disease, especially haemangioma and focal nodular hyperplasia.
- Haemochromatosis.
- Gallbladder disease.
- Biliary duct obstruction.
- Evaluation of liver infiltrants such as iron or fat.

Equipment

- Body coil/volume torso array or multi-coil.
- RC bellows.
- Ear plugs.
- Pe gating leads if required.

Patient positioning

The patient lies supine on the examination couch with the RC bellows (if required) securely attached. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment

11
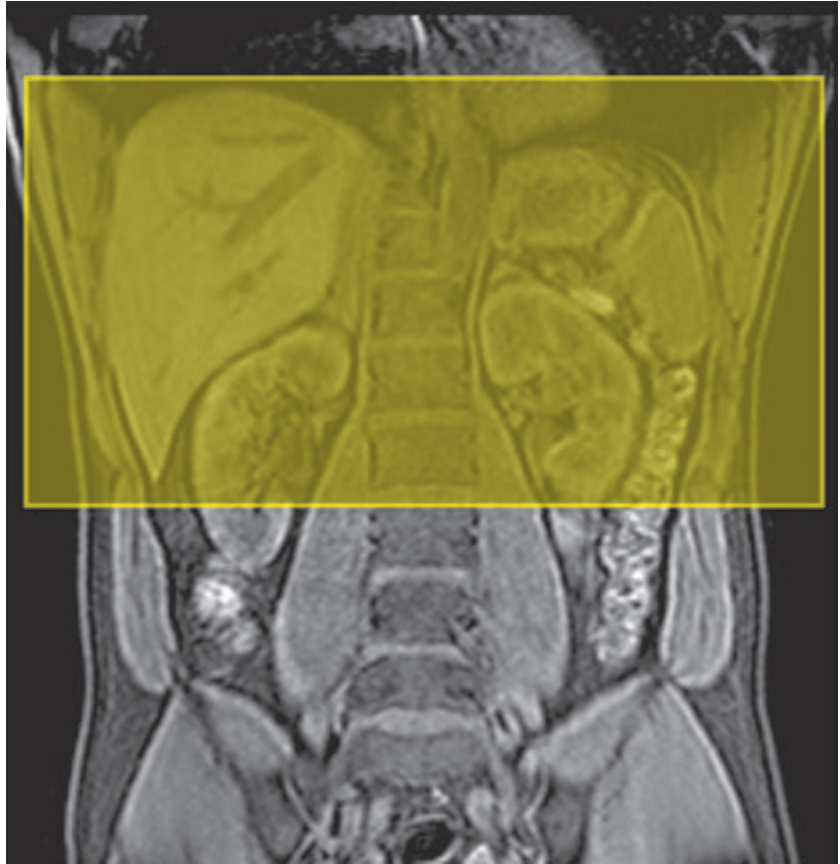
Figure 11.2 Coronal SE T1 weighted image through the abdomen demonstrating slice prescription boundaries and orientation for axial imaging of the liver.

light passes through the level of the third lumbar vertebra, or the lower costal margin.

Suggested protocol

Coronal breath-hold incoherent (spoiled) GRE/SE T1 (Figure 11.2)

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gap are prescribed relative to the vertical alignment light, from the posterior abdominal muscles to the anterior abdominal wall. The area from the pubis symphysis to the diaphragm is included in the image.

P 60 mm to A 40 mm

Axial SE/FSE/incoherent (spoiled) GRE T1 +/− in and out of phase (Figures 11.3 and 11.4)

As for Coronal T1, **except** prescribe slices from the inferior margin of the liver to the diaphragm.
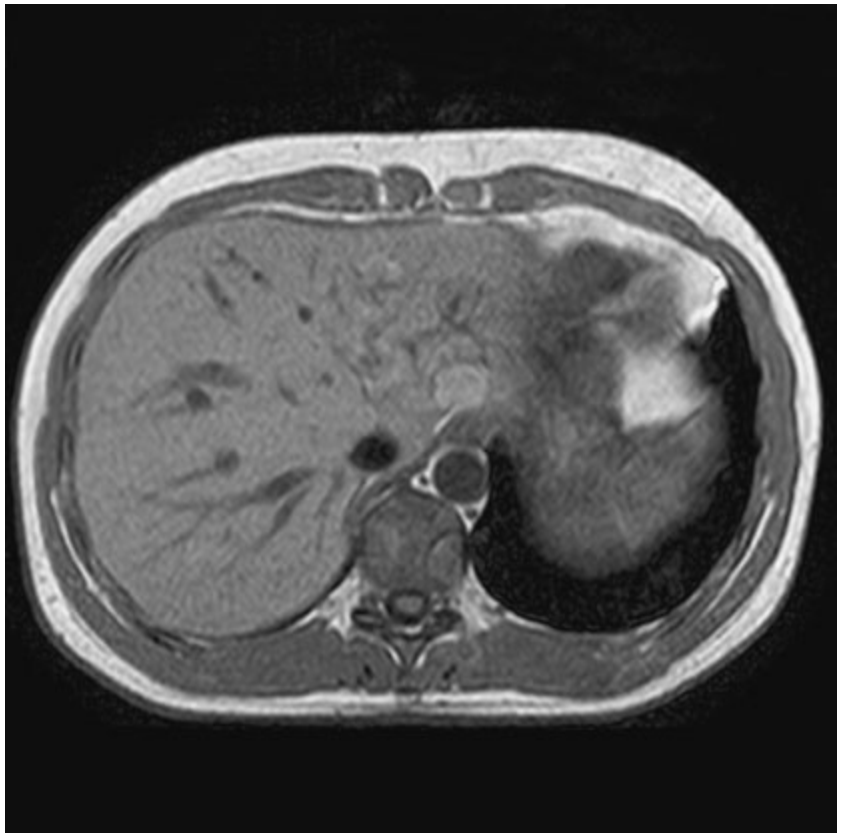
Figure 11.3 Axial FSE T1 weighted image through the liver.
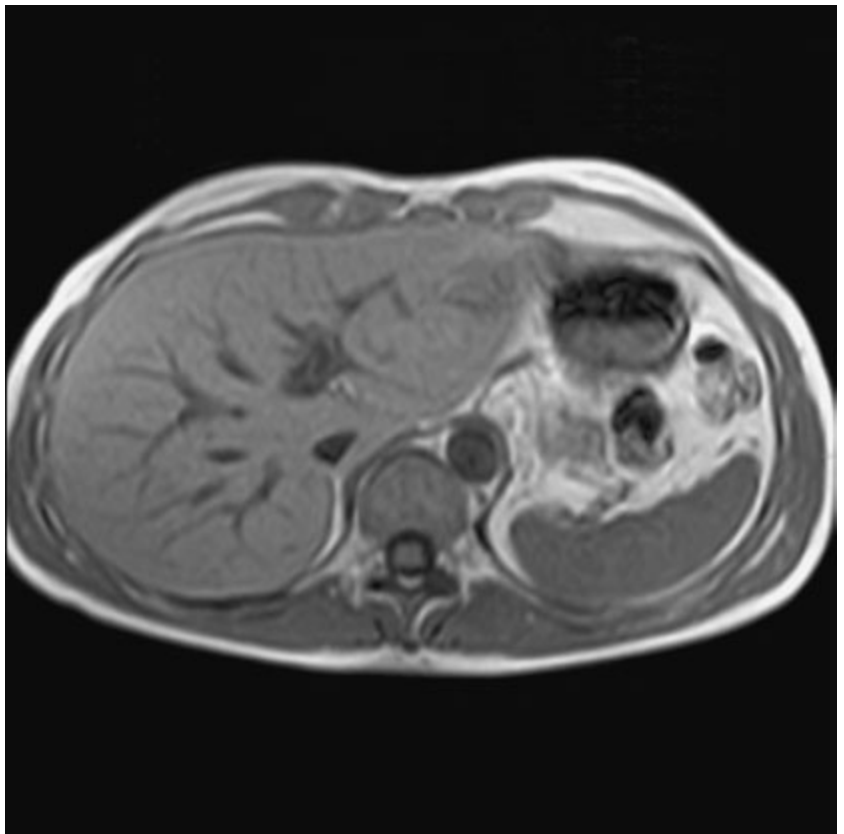
Figure 11.4 Axial incoherent (spoiled) T1 weighted breath-hold image of the liver.

Figure 11.5 Axial fast GRE T2* through the liver.

Delayed scans after contrast enhancement using chemical/spectral presaturation techniques are sometimes necessary to evaluate arterial and venous phases.

Axial SE/FSE T2 or GRE T2* (Figures 11.5 and 11.6)

Slice prescription as for Axial T1.

Axial SE/FSE/breath-hold incoherent (spoiled) GRE T1 + contrast

Slice prescription as for Axial T1.

Additional sequences

SS-FSE (MRCP) (Figure 11.7)

This sequence provides images in which only fluid-filled spaces such as the gall bladder and biliary ducts return signal. It is necessary to use very long TEs and TRs to effectively nullify the signal from all tissues except those that have long T2 decay times. TEs in excess of 200 ms and TRs of more than 10 s are required (see also *Pancreas* and *Salivary glands*). If SS-FSE is unavailable then an FSE sequence may be substituted.

Figure 11.6 Axial SS-FSE T2 through the liver.

Figure 11.7 Coronal SS-FSE image of the gallbladder (MRCP). Very long values of TR and TE were used to acquire images in which only fluid is seen.

SS-FSE/GRE-EPI/SE-EPI/diffusion imaging

The use of real-time imaging has applications in the liver and biliary system. This includes biopsies and thermal ablations of liver lesions under real-time MR control. In addition, diffusion and perfusion techniques of the liver have been developed that may negate the use of contrast agents in the future. DWI images are overlaid onto T1 weighted acquisitions. The DWI image set provides pathology information, whereas the T1 weighted acquisition provides anatomical data. The images produced are not dissimilar to a PET/CT scan. In addition diffusion tensor imaging used in conjunction with parallel imaging techniques enables differentiation of benign from malignant hepatic lesions and may also assist in the quantification of hepatic fibrosis.

Image optimization

Technical issues

The inherent SNR and CNR of the abdominal contents are usually excellent due to their high proton density, and the use of a torso array coil increases this even further. In addition parallel imaging techniques using multi-array coils reduce scan time significantly. Due to respiratory artefact, RC or respiratory triggering may be necessary. Alternatively, breath-hold techniques may be used to suspend respiratory motion. In axial T1 sequences, it is necessary to shorten the TR to less than 400 ms in SE sequences as this is considered the optimum value for demonstrating liver contrast. As the slice number available per acquisition is reduced with a short TR, two or three acquisitions may be required to cover the whole liver. Two FSE sequences using TEs of 80 ms and 160 ms are required to characterize haemangiomas, which retain a high signal intensity on late echo images.

Artefact problems

The main source of artefact in the liver is motion caused by respiration, flow and peristalsis. RC or respiratory triggering is often required, especially on the superior axial slices, due to the proximity of the diaphragm. However, breath-hold techniques may also be utilized. Pe gating is sometimes used but it often increases the scan time, especially if the patient's heart rate is slow or cardiac output poor, so that the system cannot trigger efficiently off each R wave. Commonly, Pe gating does not significantly increase image quality and only serves to lengthen the scan time. Under these circumstances it is advisable to dispense with it. Spatial presaturation pulses placed S and I to the FOV are necessary to decrease flow motion artefact in the aorta and IVC. GMN also minimizes flow artefact but, as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. Bowel motion is often a problem on the lower axial slices of the liver, whereas gastric motion artefact

11

is sometimes evident on the more superior slices. Antispasmodic agents, given IV, IM or subcutaneously prior to the examination, effectively reduce this.

Patient considerations

Careful explanation of the procedure is important. Ensure that the patient is as comfortable as possible. Some antispasmodic agents given IM may cause nausea but fruit juice given after the study can alleviate this.

Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is often beneficial to demonstrate liver metastases. Weighting depends on the type of contrast media used. T1 shortening agents such as gadolinium require T1 weighted post-contrast scans. These can be acquired in conjunction with chemical/spectral presaturation pulses and acquired in multiple phases to evaluate the dynamic contrast enhancement characteristics of hepatic lesions. T2 weighting is necessary after injection of superparamagnetic T2 shortening (liver specific) agents (see *Contrast agents* in Part 1). Scans should be delayed for approximately 1 hour after injection to allow time for uptake of contrast by the liver. The use of contrast and dynamic imaging to visualize liver vasculature and the biliary system is gaining in popularity. Oral and rectal contrast agents, for evaluation of gastrointestinal disease, are also used (see *Contrast agents* in Part 1).

11

Kidneys and adrenal glands

Basic anatomy (Figure 11.8)
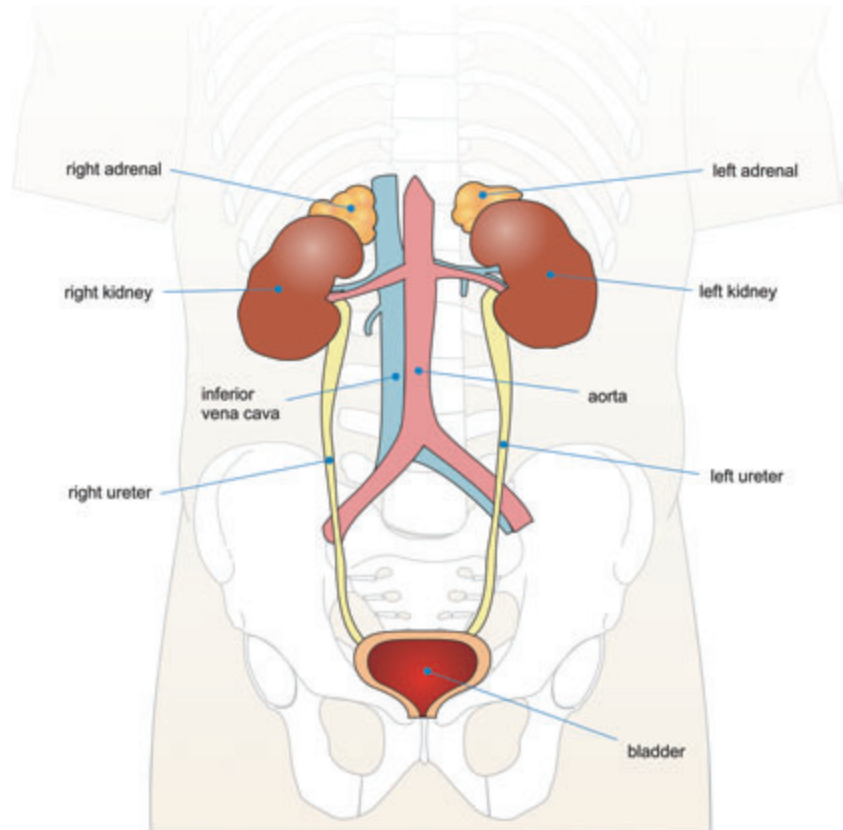
Figure 11.8 The urinary system and its vascular supply.

Common indications

- Adrenal masses and haemorrhage.
- Renal masses and haemorrhage.
- Renal cell carcinoma.
- Renal transplant rejection.
- Ureteric obstruction.

Equipment

- Body coil/multi-phased array or multi-coil array.
- RC bellows.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with the RC bellows securely attached (if required). The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the third lumbar vertebra, or the lower costal margin. The kidneys are generally located about four fingers inferior to the xiphoid.

Suggested protocol

Coronal breath-hold fast incoherent (spoiled) GRE/SE/FSE T1
(Figure 11.9)

Acts as a localizer if three-plane localization is unavailable. Alternatively it can be used as a diagnostic sequence. Medium slices/gap are prescribed on either side of the vertical alignment light, from the posterior abdominal

11
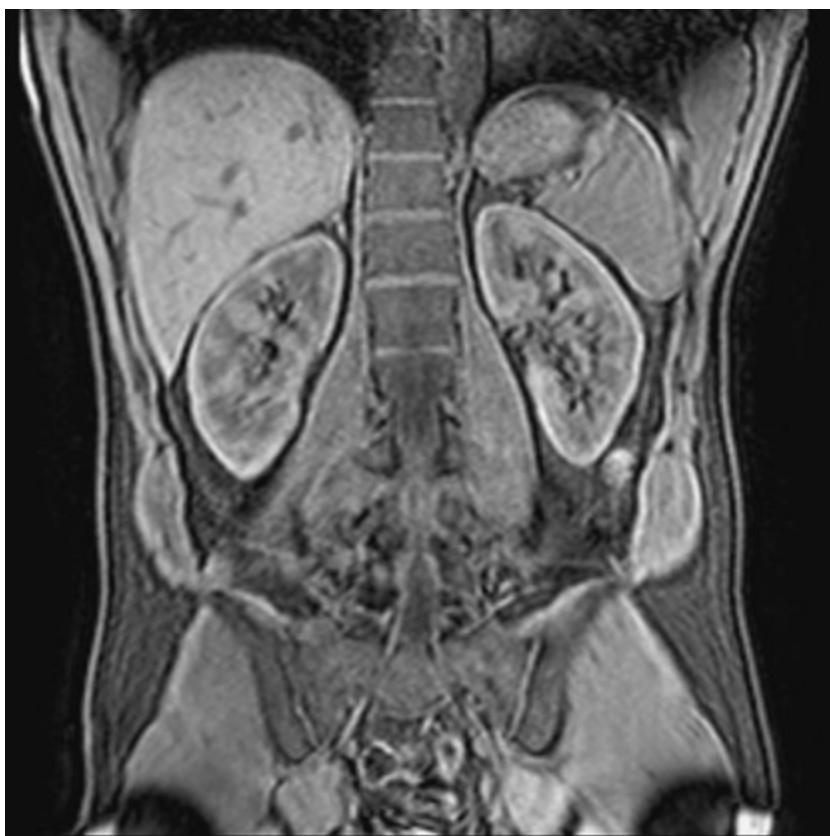
Figure 11.9 Coronal incoherent (spoiled) GRE T1 weighted image through the abdomen demonstrating the kidneys.
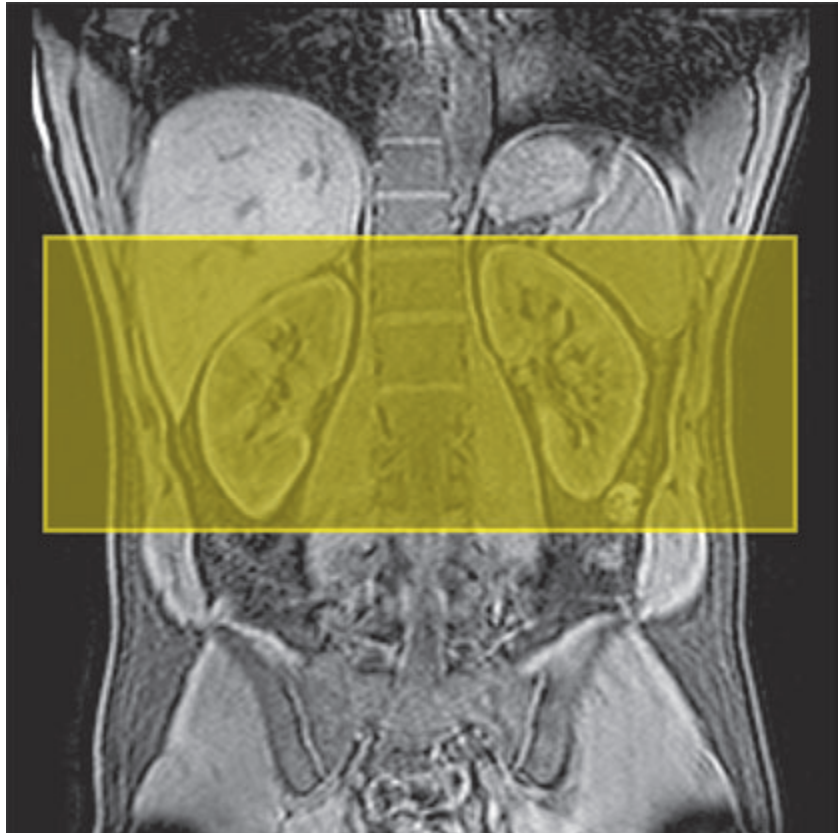
Figure 11.10 Coronal incoherent (spoiled) GRE T1 weighted through the abdomen demonstrating slice prescription boundaries and orientation for axial imaging of the kidneys.

muscles to the anterior abdominal wall. The area from the pubis symphysis to the diaphragm is included in the image.

P 60 mm to A 40 mm

Axial incoherent (spoiled) GRE T1 in and out of phase +/− contrast +/− chemical/spectral presaturation (Figures 11.11, 11.13 and 11.14)

As for Coronal SE/FSE T1, **except** medium slices/gap are prescribed from the inferior margin of the kidneys to the superior aspect of the adrenals (Figure 11.10). The coronal plane may also be useful depending on lesion location. Slices may also be offset to specifically image the adrenals (Figure 11.12).

Additional sequences

MR urography

Either FSE or SS-FSE sequences may be used with very long TEs and TRs to produce heavily T2 weighted images in which only fluid that has a very

Figure 11.11 Axial incoherent (spoiled) GRE T1 weighted image acquired with a TE when fat and water are in phase (above) and out of phase (below).

11
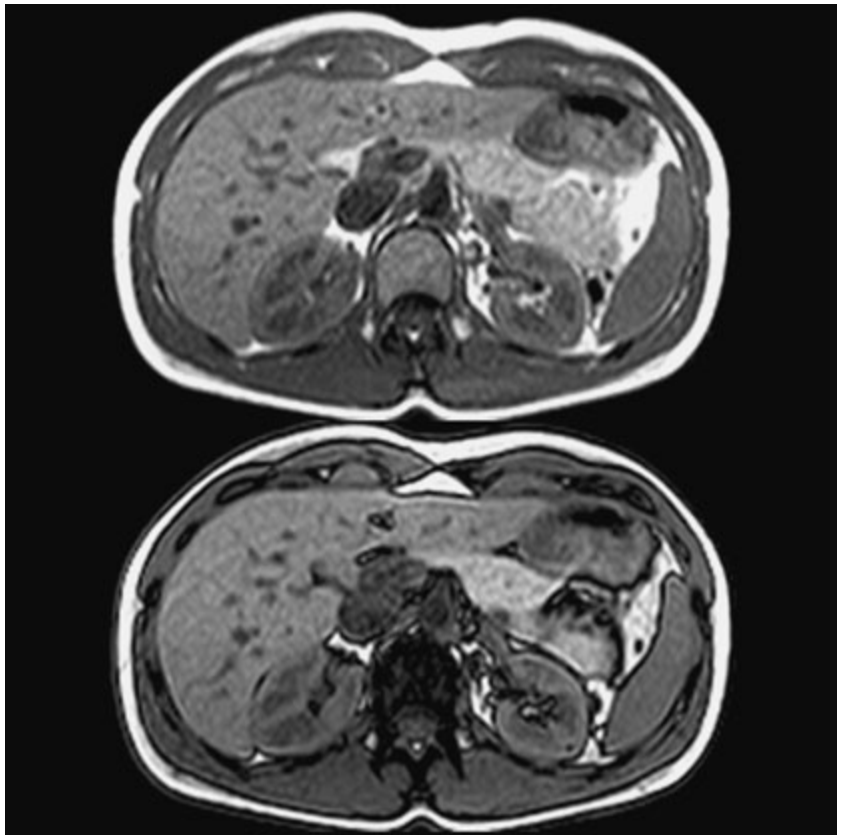
Figure 11.12 Coronal incoherent (spoiled) GRE T1 weighted through the abdomen demonstrating slice prescription boundaries and orientation for axial imaging of the adrenals.
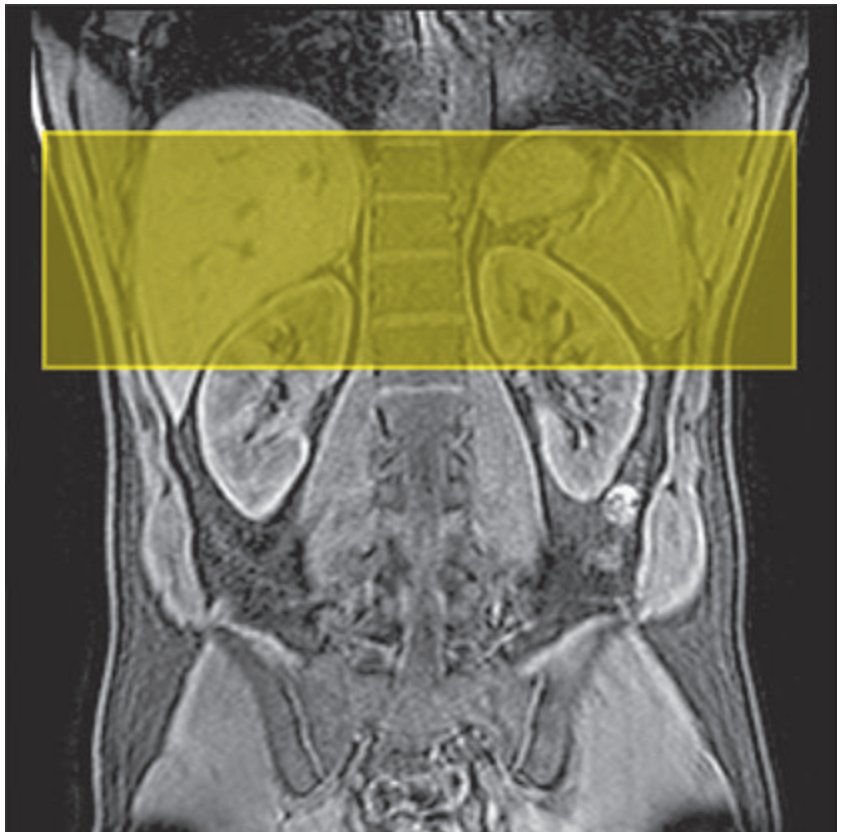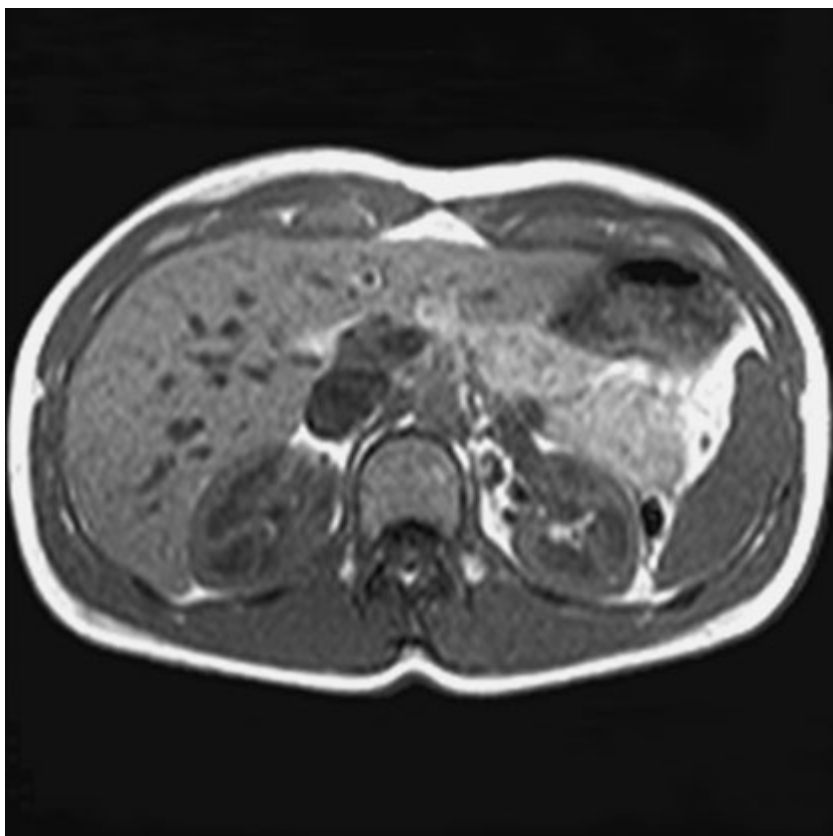
Figure 11.13 Axial fast incoherent (spoiled) GRE T1 weighted image through the kidneys.
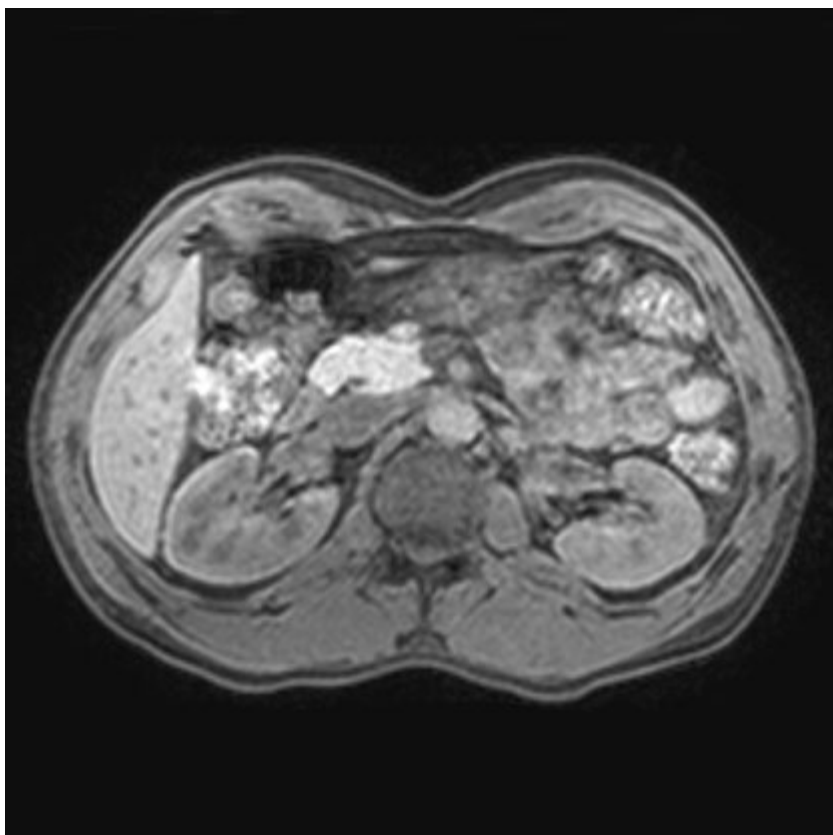
Figure 11.14 Axial incoherent (spoiled) GRE T1 with chemical/spectral presaturation.

long T2 decay time is seen. It has applications in the biliary system (see also *Liver and biliary system* earlier in this chapter) and in the salivary gland. It may also be of use in the urinary system to visualize the renal collecting system, the ureters and the bladder.

Diffusion imaging

DWI using SS-EPI acquisition in conjunction with parallel imaging techniques may be useful in the differentiation of malignant adrenal lesions from hyperplasia or adenomas and renal cysts from renal cell carcinomas.

Image optimization

Technical issues

The inherent SNR and CNR of the abdominal contents are usually excellent due to their high proton density, and the use of a torso array coil increases this even further. In addition, parallel imaging techniques using multi-array coils reduce scan times significantly. Spatial resolution is important, especially when imaging relatively small structures such as the kidneys and adrenal glands, which therefore require thin slices/gap. However, this is often difficult to achieve when using the body coil, a large FOV and in the presence of respiratory and flow artefact. The use of a torso array coil greatly improves resolution in the abdomen. In addition, parallel imaging techniques can be used to improve resolution whilst keeping scan times short. SE sequences usually produce the best contrast in the abdomen, but result in fairly lengthy scan times. For this reason, breath-hold GRE or SS-FSE sequences are often preferred. FSE used in conjunction with a rectangular/asymmetric FOV allows PD and T2 images to be obtained in a shorter scan time.

Artefact problems

The main source of artefact in this area is from respiratory movement and flow in the aorta and the IVC. RC or respiratory triggering is often required and significantly reduces respiratory ghosting. Alternatively, breath-hold techniques may be utilized. Spatial presaturation pulses placed S and I to the FOV are necessary to reduce flow motion artefact arising from the aorta and IVC. As the kidneys and adrenals are retroperitoneal structures, a spatial presaturation band brought into the FOV and placed over the anterior abdominal wall reduces respiratory artefact significantly without obscuring important anatomy. GMN also minimizes flow and, in some cases, respiratory motion but it increases the signal in vessels and the minimum TE.

Chemical shift artefact is often troublesome in the kidneys, especially at higher field strengths. This is due to retroperitoneal fat being adjacent to fluid-filled kidneys. Narrowing the receive bandwidth increases this

11

artefact but, if used in conjunction with fat suppression techniques, results in a significant improvement in SNR and a reduction in chemical shift. However, this strategy increases the minimum TE and is therefore reserved for T2 weighted sequences. Bowel motion is also troublesome but is effectively reduced by the administration of antispasmodic agents given IV, IM or subcutaneously prior to the examination.

Patient considerations

Careful explanation of the procedure is important. Ensure that the patient is as comfortable as possible. Some antispasmodic agents given IM may cause nausea but fruit juice given after the study can alleviate this. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is sometimes useful in conjunction with dynamic imaging to visualize the uptake of contrast in the kidneys (see *Dynamic imaging* under *Pulse sequences* in Part 1). Vascular imaging of the renal arteries is a common technique discussed later (see *Vascular imaging* later in this chapter). Contrast may also be necessary to increase the conspicuity of the adrenal glands. Recently functional imaging of the kidneys after the administration of macro molecular contrast agents have been advocated in the evaluation of a variety of renal diseases. These agents are almost totally excreted by the kidneys, thereby improving the conspicuity of lesions that have different perfusion characteristics.

Pancreas

Basic anatomy (Figure 11.15)
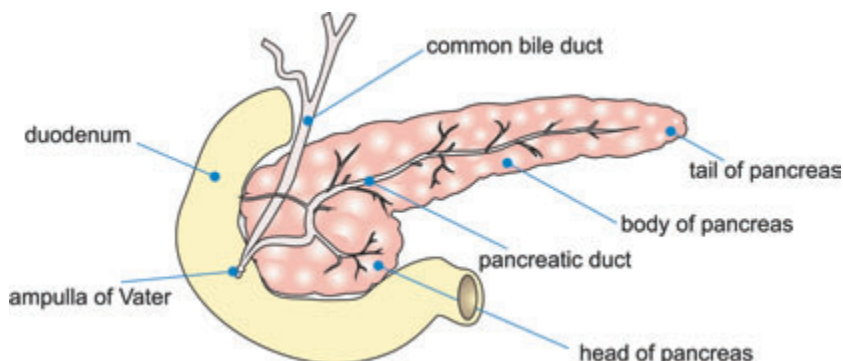
Figure 11.15   The pancreas.

Common indications

- Pancreatic tumours.
- Pancreatic duct obstruction.

Equipment

- Body coil/multi-phased array/multi-array coil.
- RC bellows.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with the RC bellows securely attached. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the third lumbar vertebra, or the lower costal margin.

Suggested protocol

Coronal breath-hold fast incoherent (spoiled) GRE/SE T1
(see Figure 11.9)

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gap are prescribed on either side of the

11
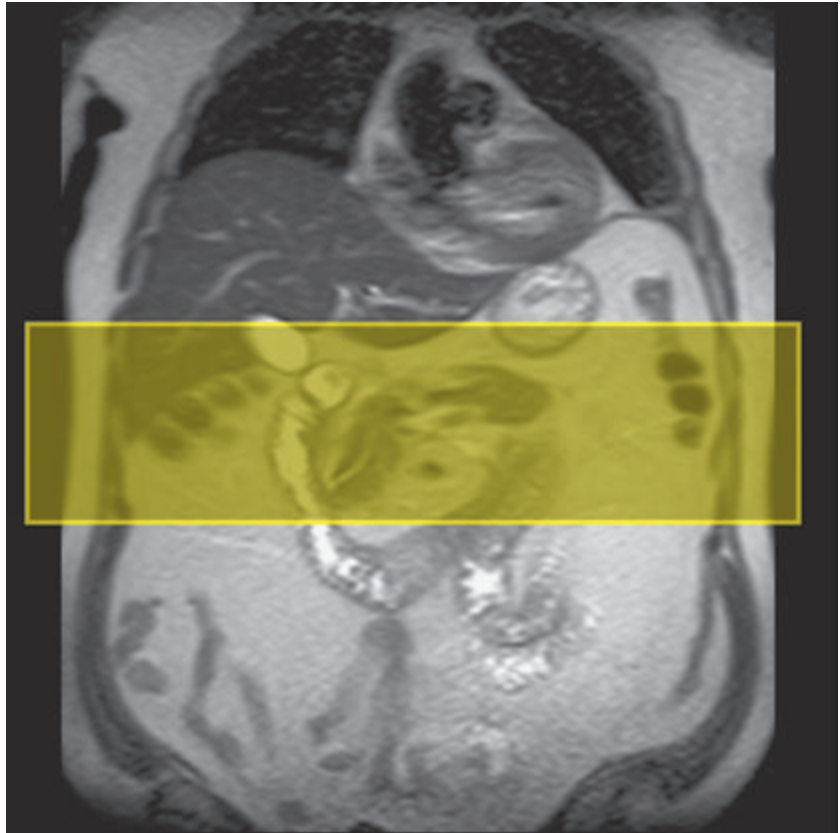
Figure 11.16   Coronal FSE T1 weighted image through the abdomen demonstrating slice prescription boundaries and orientation for axial imaging of the pancreas.

11

vertical alignment light, from the posterior abdominal muscles to the anterior abdominal wall. The area from the pubis symphysis to the diaphragm is included in the image.

P 60 mm to A 40 mm

Axial FSE/SE/breath-hold fast incoherent (spoiled) GRE T1 +/− chemical/spectral presaturation/in and out of phase imaging

As for Coronal T1, except thin slices/gap are prescribed through the pancreas (Figure 11.16).

Axial FSE/SS-FSE T2 (Figures 11.17 and 11.18)

Slice prescription as for Axial T1.

Axial breath-hold fast incoherent (spoiled) GRE T1 (Figure 11.19)

For visualization of small pancreatic tumours +/− contrast.
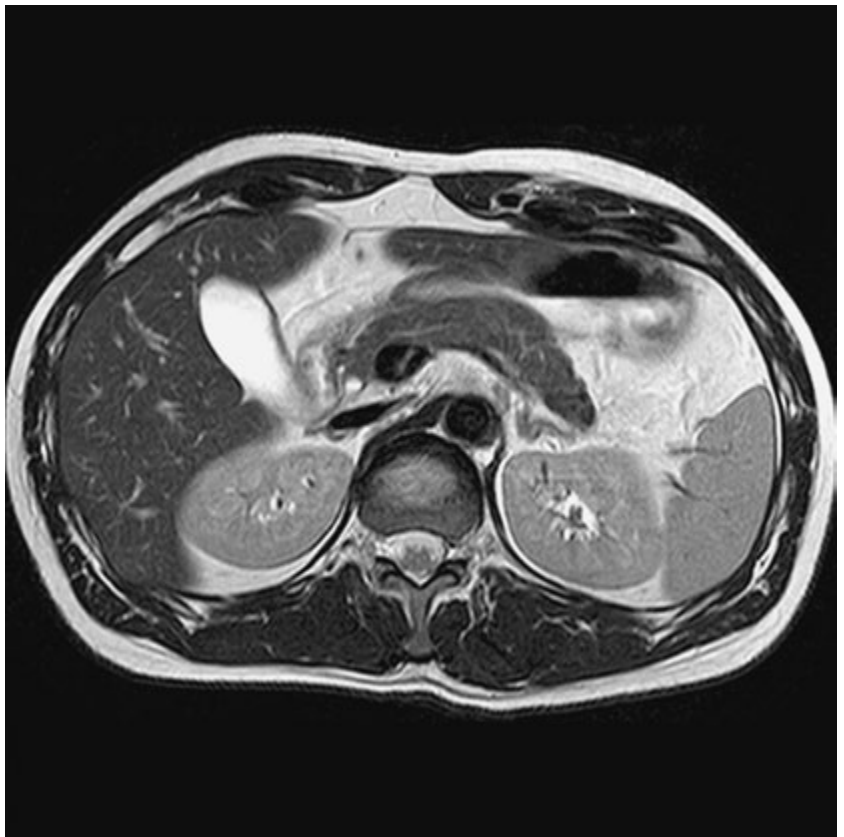
Figure 11.17 Axial high resolution FSE T2 of the pancreas.
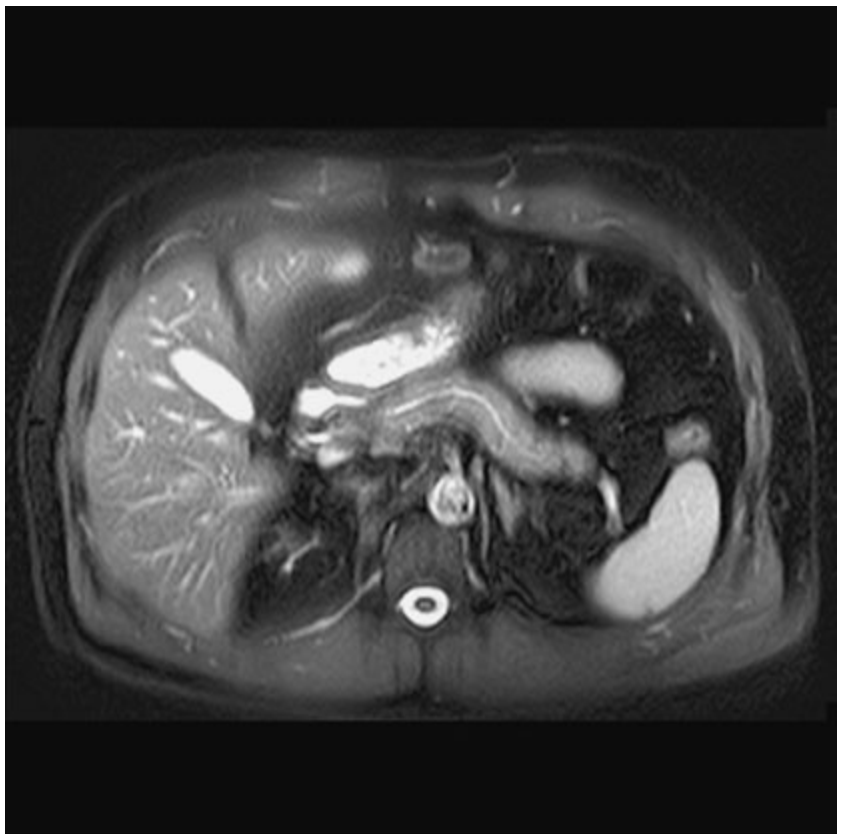
Figure 11.18 Axial SS-FSE T2 of the pancreas during free breathing.

11

Figure 11.19   Axial fast incoherent (spoiled) T1 weighted image of the pancreas.

SS-FSE (Figures 11.20 and 11.21)

As for MRCP technique described in the biliary system. Demonstrates pancreatic duct obstruction.

Diffusion imaging

Diffusion imaging used in conjunction with parallel imaging techniques may be useful to detect pancreatic adenocarcinoma and for differentiation from benign and cystic lesions.

Image optimization

Technical issues

The inherent SNR and CNR of the abdominal contents are usually excellent due to their high proton density, and the use of a torso array coil increases this even further. In addition, parallel imaging techniques using multi-array coils reduce scan times significantly. Spatial resolution is also

Figure 11.20 MRCP of the pancreatic duct.
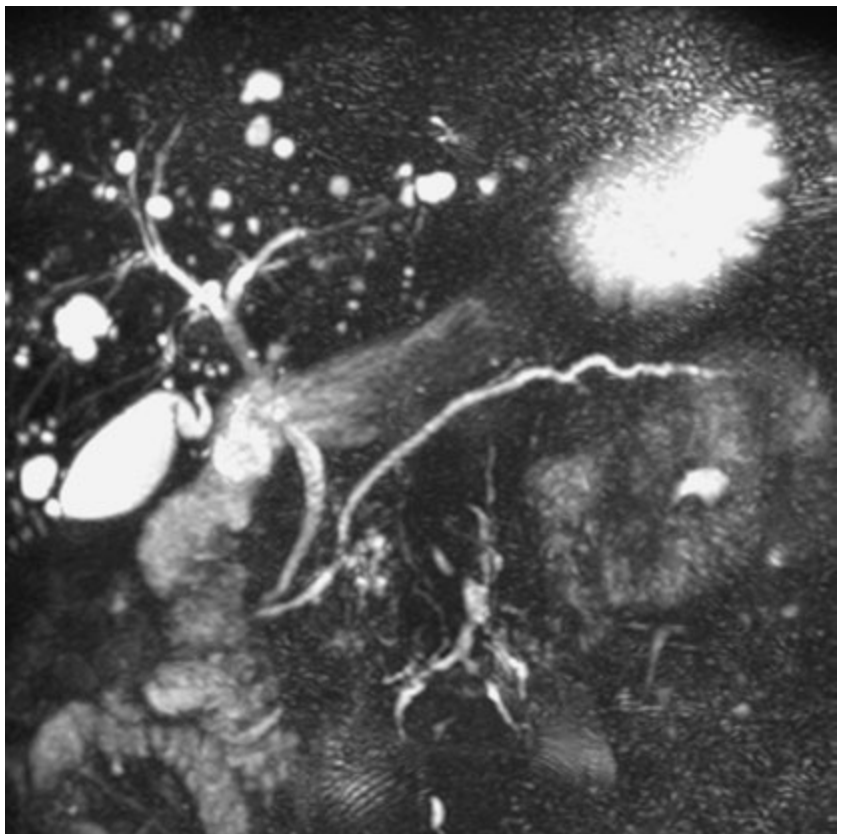
Figure 11.21 MRCP of the pancreatic duct and the rest of the biliary system.

important, especially when imaging relatively small structures such as the pancreas that require thin slices/gap. However, good resolution is often difficult to achieve when using the body coil and a large FOV, and in the presence of respiratory and flow artefact. A torso phased array coil greatly improves the SNR that can then be traded for resolution. In addition, parallel imaging techniques can be used to improve resolution whilst keeping scan times short. SE sequences usually produce the best contrast in this region, but result in fairly lengthy scan times and therefore FSE is usually used.

Artefact problems

The main source of artefact in this region is from respiratory and flow motion in the aorta and IVC. RC or other respiratory gating techniques are often required and significantly reduce respiratory ghosting. Alternatively, breath-hold techniques may be utilized. Spatial presaturation pulses placed S and I to the FOV are necessary to reduce flow motion artefact in the aorta and IVC. GMN also minimizes flow motion but, as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. Additional shimming may be required before chemical/spectral presaturation sequences. Gastric and bowel motion is also troublesome in this area due to the proximity of the stomach and the duodenum to the pancreas. This artefact is effectively reduced by the administration of antispasmodic agents given IV, IM or subcutaneously prior to the examination.

Patient considerations

Careful explanation is essential if breath-holding sequences are to be performed. Some antispasmodics given IM may cause nausea, which can be remedied by giving the patient fruit juice after the scan. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

11

Contrast usage

Contrast is often necessary in conjunction with dynamic imaging to visualize small pancreatic lesions. Positive and negative oral contrast agents to delineate bowel, and therefore the pancreas, can be useful. Recently studies have been performed using secretin as an enhancement agent. This stimulates the release of fluid into the pancreatic duct, thereby improving visualization on T2 weighted images. There may also be a role for secretin in the evaluation of pancreatic function.

Vascular imaging

Basic anatomy (Figure 11.22)
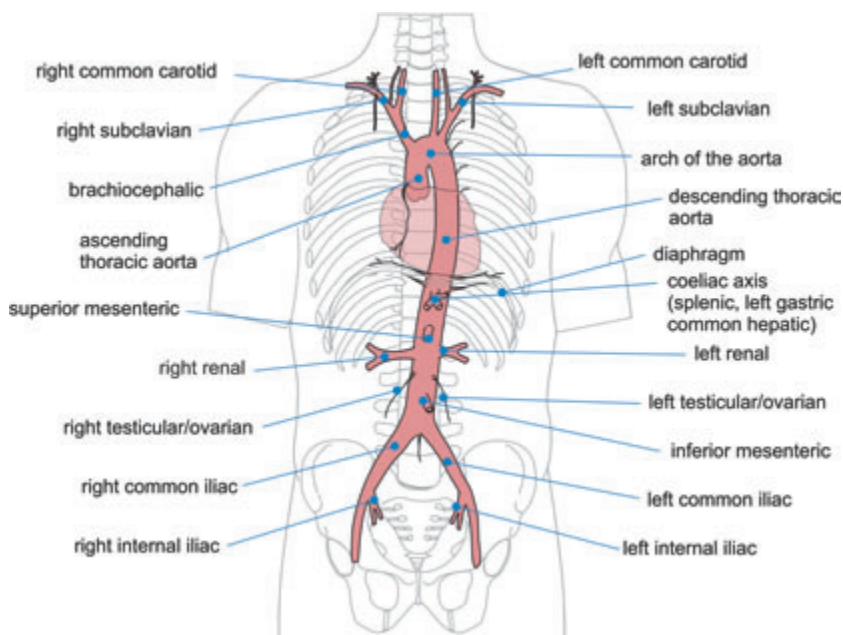
Figure 11.22 Anterior view of the abdomen showing arterial vessels.

Common indications

- Pre-operative assessment of aortic thrombus, occlusion, stenosis and dissection.
- Demonstration of major vascular anomalies.
- Portal or hepatic vein thrombosis.
- Evaluation of hepatic vascular anatomy prior to tumour resection.
- Renal vein thrombosis.
- Assessment of vasculature prior to and after renal transplantation.

Equipment

- Body coil/volume torso array/multi-array coil.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch and is positioned so that the longitudinal alignment light lies in the midline, and the horizontal

alignment light passes through the level of the third lumbar vertebra, or the lower costal margin.

For localized imaging, the horizontal alignment light passes through the vessel to be imaged.

Suggested protocol

MRA is now a well established technique but has its limitations. Coronal or sagittal breath-hold incoherent (spoiled) GRE localizers may be followed by axial 2D or 3D TOF-MRA that are then reconstructed in a number of planes. Although 2D TOF-MRA provides coverage, Venetian blind artefact and poor resolution reduce image quality. 3D TOF-MRA provides better resolution but less coverage (see *Pulse sequences* in Part 1). Therefore, alternative methods of visualizing abdominal vascular anatomy such as breath-hold incoherent (spoiled) GRE T1 imaging before, during, and after administration of a bolus of contrast and SE black blood and GRE bright blood sequences are important.

CE-MRA of the abdominal aorta and renal arteries is a well established technique. A small bolus of gadolinium is given via cannula in the antecubital fossa, the acquisition timed to the arrival of the bolus in the area of interest (see *Dynamic imaging* in Part 1). Fast incoherent (spoiled) GRE is the sequence of choice and the coronal plane is used (Figure 11.23).

When used in conjunction with SE sequences, spatial presaturation pulses produce black blood. If a signal persists in a vessel it may indicate either slow flow or occlusion. When used in conjunction with GRE sequences, GMN produces bright blood. If a signal void is seen within the vessel, it may indicate either slow flow or occlusion.

Image optimization

Technical issues

The SNR and CNR in vascular imaging of the abdomen are improved by the use of phased array coils. In addition parallel imaging techniques allow for reduced scan times or improved resolution. However, when contrast enhancement is used images can be acquired rapidly at the expense of SNR and CNR, as gadolinium provides enough contrast to visualize vessel structure. Additional options such as centric K space filling or propeller imaging (where K space is filled in rotating strips) permit improved temporal resolution when the contrast agent is in the imaging volume.

If conventional MRA is used, to optimize vessel contrast on TOF-MRA sequences, spatial presaturation bands are placed S to the FOV to visualize the IVC, and I to the FOV to demonstrate the aorta. Vessel conspicuity is increased by the implementation of GMN, which increases signal in vessels, and MT, which suppresses background signal (see *Pulse sequences* in Part 1).

Figure 11.23 Coronal breath-hold incoherent (spoiled) GRE T1 weighted image during dynamic contrast enhancement.

Artefact problems

Respiratory motion is a potential source of artefact in these examinations. Venetian blind artefact, commonly seen in 2D TOF-MRA sequences, is also caused by respiration and pulsatile flow (see *Vascular imaging* in Part 1). The implementation of breath-hold techniques is often, therefore, necessary. Gated TOF-MRA and the utilization of travelling presaturation bands may be implemented to reduce pulsatile artefacts.

Patient considerations

Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

The use of MRA, in conjunction with contrast enhancement to improve image quality, is an important technique. Enhancing agents shorten the T1 of blood, thereby increasing vessel contrast in sequences that are sensitive to T1. In addition, agents that remain in the blood for delayed

11

vascular imaging (blood pool agents) are sometimes used. For contrast enhanced MRA studies, early acquisitions demonstrate the arterial phase, mid-term acquisitions the capillary phase, and later acquisitions the venous phase. Therefore timing of each acquisition after injection is important. This is usually automated by the system where data acquisition is triggered by an increase in signal detected by a navigator as the gadolinium arrives in the aorta.

11

12

Pelvis

12

Table 12.1   Summary of parameters. The figures given are general and should be adjusted according to the system used (Table 2.1)

Spin echo (SE)

short TE	min to 30 ms
long TE	70 ms +
short TR	300−600 ms
long TR	2000 ms +

Fast spin echo (FSE)

short TE	min–20 ms
long TE	90 ms +
short TR	400−600 ms
long TR	4000 ms +
short ETL	2−6
long ETL	16 +

Inversion recovery (IR) T1

short TE	min–20 ms
long TR	3000 ms +
medium TI	200−600 ms
short ETL	2−6

STIR

long TE	60 ms +
long TR	3000 ms +
short TI	100−175 ms
long ETL	12−20

FLAIR

long TE	60 ms +
long TR	3000 ms +
long TI	1700−2200 ms
long ETL	12−20

Coherent GRE

long TE	15 ms +
short TR	≤ 50 ms
flip angle	20°−40°

Incoherent GRE

short TE	min–5 ms
short TR	≤ 50 ms
flip angle	20°−40°

Balanced GRE

TE	minimum
TR	minimum
flip angle	≥ 40°

SSFP

TE	minimum
TR	40−50 ms
flip angle	20°−40°

Slice thickness

2D	thin	2−4 mm
	medium	5−6 mm
	thick	8 mm
3D	thin	≤ 1 mm
	thick	≥ 3 mm

Slice numbers

Volumes	small	≤ 32
	medium	64
	large	≥ 128

Matrix (frequency × phase)

coarse	256 × 128 or 256 × 192
medium	256 × 256 or 512 × 256
fine	512 × 512
very fine	≥ 512 × 512

FOV

small	≤ 18 cm
medium	18−30 cm
large	≥ 30 cm

PC-MRA

2D and 3D	TE	minimum	
	TR	25−33 ms	
	flip angle	30°	
VENC venous	20−40 cm/s		
VENC arterial	60 cm/s		

NEX/NSA

short	≤ 1
medium	2−3
multiple	≥ 4

TOF-MRA

2D	TE	minimum
	TR	28−45 ms
	flip angle	40°−60°
3D	TE	minimum
	TR	25−50 ms
	flip angle	20°−30°

12

Male pelvis

Basic anatomy (Figure 12.1)

Figure 12.1   Sagittal section through the male pelvis showing midline structures.

Common indications

- Localization of undescended testicles.
- Prostatic lesions.
- Carcinoma of the bladder.
- Rectal lesions.
- Infertility.
- Impotence.

Equipment

- Body coil/phased array pelvic coil/multi-array coil. Local rectal coil for prostate imaging (can be used in conjunction with a phased/multi-array coil).
- Compression bands and foam immobilization pads.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch. Foam pads and compression bands can be applied across the patient's lower pelvis to reduce

12

respiratory and bowel motion (unless the patient cannot tolerate this). The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the pubis symphysis and the iliac crests. If a local rectal coil is used, it should be carefully inserted prior to the examination. Ensure that it is correctly positioned and fully inflated.

Suggested protocol

Coronal breath-hold fast incoherent (spoiled) GRE/SE/FSE T1
(Figure 12.2)

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gap are prescribed from the coccyx to the anterior aspect of the pubis symphysis. The area from the pubis symphysis to the iliac crests is included in the image.

P 60 mm to A 60 mm

Figure 12.2 Coronal FSE T1 weighted image through the male pelvis.

Sagittal localizers used in conjunction with a large FOV are useful to confirm the correct positioning of a rectal coil and to demonstrate nodes and bony metastases in patients with suspected prostatic carcinoma.

L 25 mm to R 25 mm

Sagittal SE/FSE T2

Demonstrates organs that lie in the midline (bladder, rectum, prostate, penis). Medium or thick slices/gap are prescribed from the left to the right pelvic side walls (Figure 12.3). Unless lymph node involvement is suspected, small structures such as the prostate require high-resolution imaging using the rectal coil and thin slices/gap prescribed through the ROI only. Chemical/spectral presaturation pulses are often necessary when using FSE sequences.

Axial SE/FSE T2 (Figure 12.5)

Demonstrates organs that lie laterally (lymph nodes). Medium or thick slices/gap are prescribed from the pelvic floor to the iliac crests (Figure 12.4). Unless lymph node involvement is suspected, small structures such
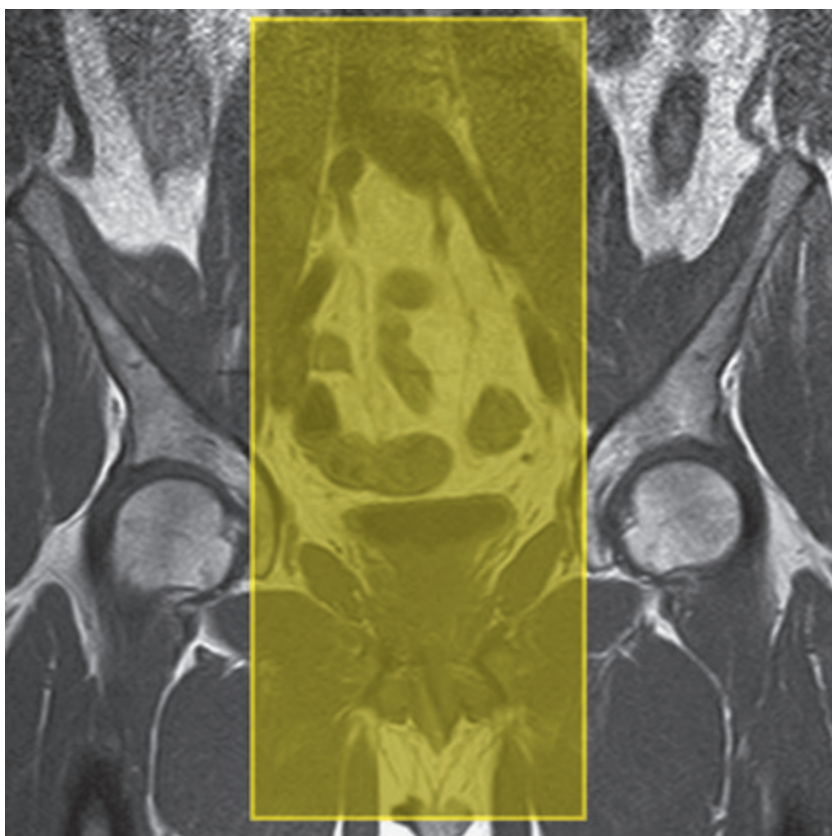
Figure 12.3 Coronal FSE T1 weighted image through the male pelvis to show slice prescription boundaries and orientation for sagittal imaging.

12
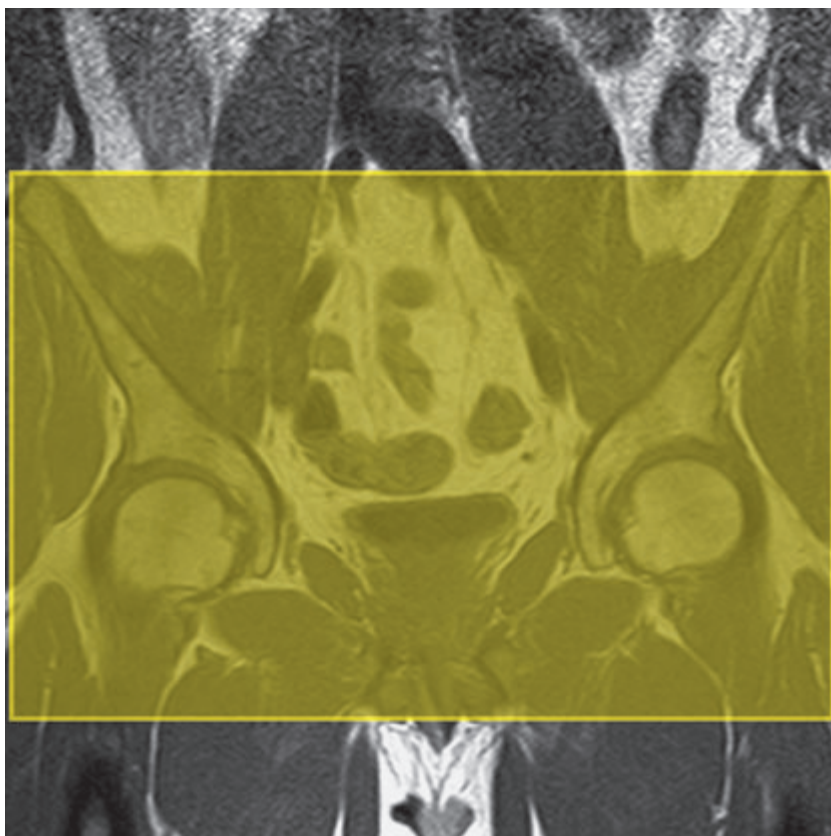
Figure 12.4 Coronal FSE T1 weighted image through the male pelvis to show slice prescription boundaries and orientation for axial imaging.
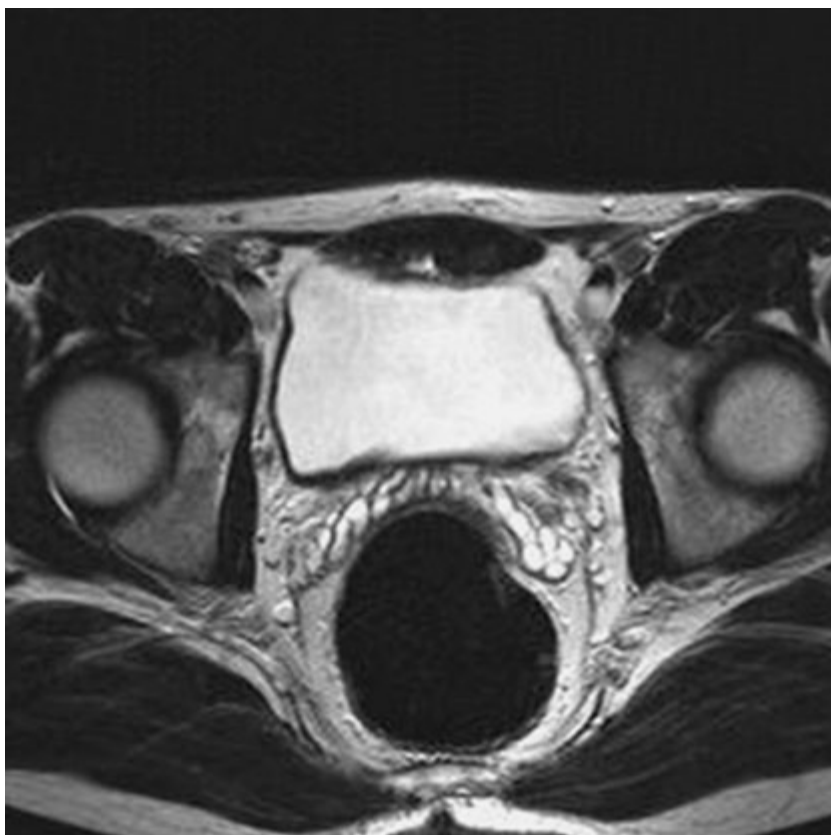
Figure 12.5 Axial FSE T2 weighted image through a normal male pelvis (rectal coil in situ).

Figure 12.6 Axial FSE T1 weighted image of a normal male pelvis.

as the prostate require high-resolution imaging using the rectal coil and thin slices/gap prescribed through the ROI only. Chemical/spectral presaturation pulses are often necessary when using FSE sequences.

Axial SE/FSE T1 (Figure 12.6)

Slice prescription as for Axial T2.

Coronal SE/FSE T2 (Figure 12.7)

Slice prescription as for Coronal SE/FSE T1.
   Chemical/spectral presaturation pulses are often necessary when using FSE sequences.

Additional sequences

Fast incoherent (spoiled) GRE T1 +/– contrast (Figure 12.8)

Rapid imaging after contrast allows dynamic evaluation of enhancing pelvic vessels responsible for potency (see *Dynamic imaging* under *Pulse sequences* in Part 1).

12
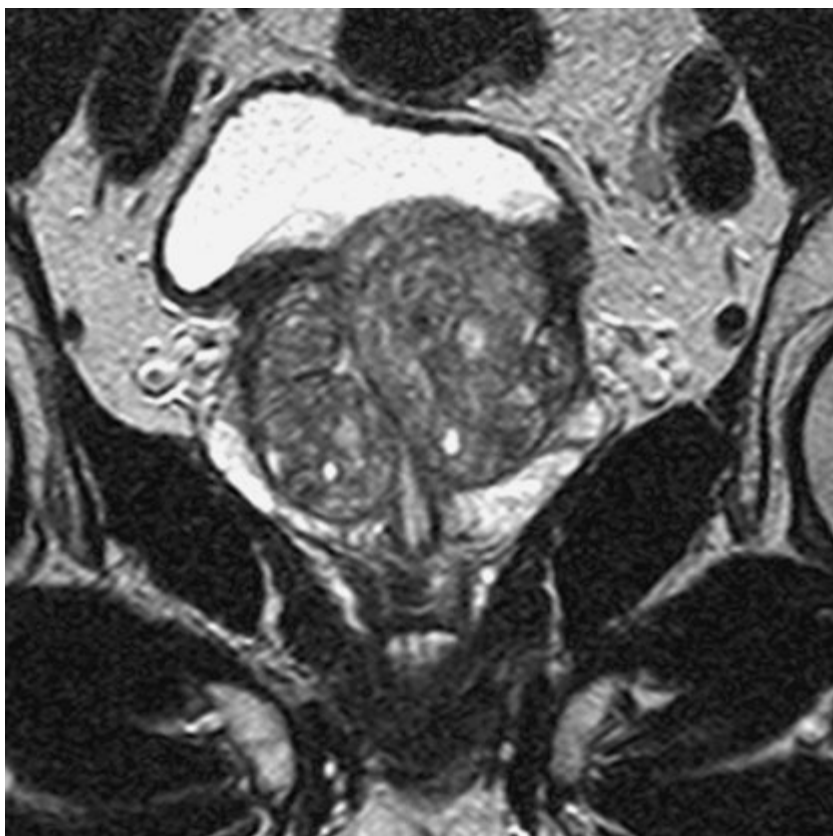
Figure 12.7 Coronal FSE T2 weighted image demonstrating an abnormal prostrate gland.
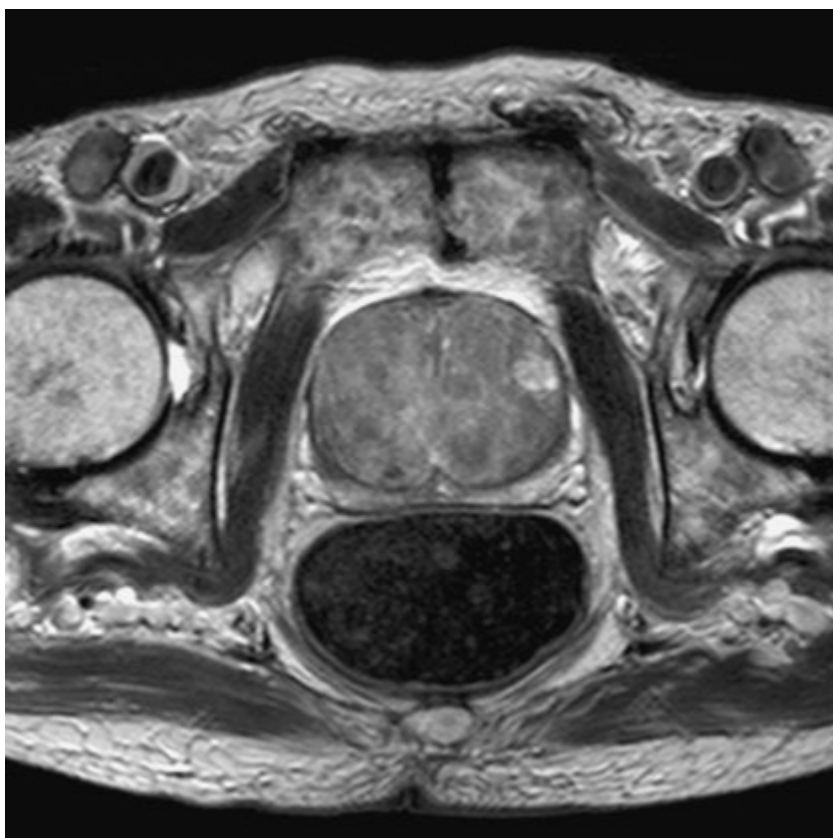
Figure 12.8 Incoherent (spoiled) GRE T1 of the prostate using a rectal coil.
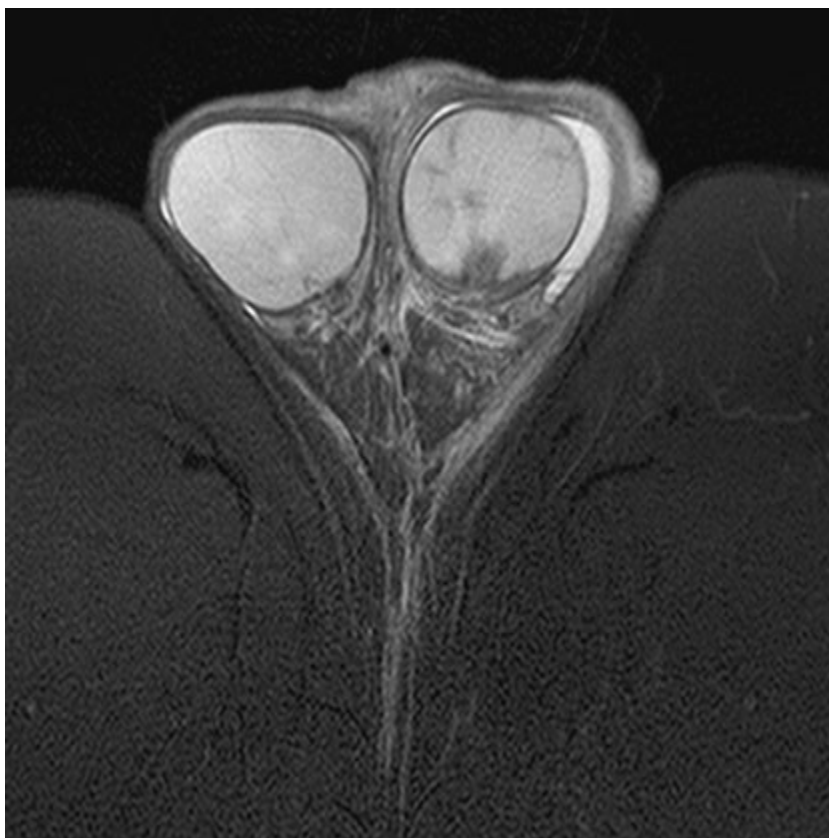
Figure 12.9 Axial FSE T2 weighted image of the scrotum acquired with a surface coil. This was performed for the evaluation of testicular carcinoma.

SS-FSE/SE-EPI/GRE-EPI/Diffusion Imaging

Real-time imaging of pelvic organs, especially the prostate, enables biopsies and laser ablations of lesions under MR control. DWI used in conjunction with parallel imaging techniques are proving useful in the differentiation of malignant from benign lesions especially in the prostate gland. In addition, small FOV high resolution images of the scrotum may be useful for the evaluation of testicular carcinoma (Figure 12.9).

Image optimization

Technical issues

The pelvis offers excellent SNR and contrast, especially when phased array, multi-array or local rectal coils are used. As a result, spatial resolution is easily obtainable without compromising signal. In addition the use of parallel imaging techniques can significantly reduce scan times or increase resolution. FSE provides very good results in the pelvis, as respiration and bowel motion are less troublesome than in the abdomen. In addition, a rectangular/asymmetric FOV is routinely implemented with the long axis of the rectangle S to I in the sagittal images, and R to L in the

12

axials. The combination of FSE, a rectangular/asymmetric FOV, and local or phased array or multi-array coils (where a small FOV is implemented) enables the acquisition of very fine matrix sizes in conjunction with a short scan time.

Oversampling is sometimes not available with a rectangular/asymmetric FOV. If so, ensure that the FOV is large enough to incorporate all the pelvis, or apply spatial presaturation bands A and P to reduce aliasing. If SE is selected, a fine matrix may still be utilized to provide good spatial resolution and a fairly short scan time. Fat suppression techniques are often beneficial, especially on FSE T2 images.

Artefact problems

Bowel motion is reduced by compression and administering antispasmodic agents IV, IM or subcutaneously prior to the examination. Compression also reduces respiratory motion by encouraging the patient to breathe from their upper abdomen and chest, rather than their pelvis. Spatial presaturation pulses applied S and I to the FOV reduce flow motion artefact in the IVC, aorta and iliac vessels. GMN further reduces flow artefact but, as it increases signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. Additional shimming may be required before chemical/spectral presaturation sequences.

When imaging with a local rectal coil, rectal spasm commonly causes artefact. The phase and frequency axes are swapped on the sagittal and axial images so that this artefact does not obscure the prostate. In addition, oversampling is often necessary on these small FOV images, as anatomy exists outside the FOV in the phase direction, but within the signal-producing volume of the coil.

Patient considerations

Some patients may not be able to tolerate compression, especially if they have had recent abdominal surgery. Compression can also make a claustrophobic patient feel more trapped. Under these circumstances, placing the patient prone has the same (albeit lesser) effect as compression. In addition, if the ROI lies posteriorly (e.g. fistulae in the buttocks), placing the patient prone positions the ROI nearer to magnetic isocentre, thereby increasing image quality. Some antispasmodic agents given IM may cause nausea but fruit juice given after the study can alleviate this. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be given to enhance the conspicuity of certain lesions, especially in examinations of the prostate, pelvis masses and vasculature. Oral or rectal contrast agents including air (administered carefully) to label and demonstrate the rectum and lower gastrointestinal tract are sometimes used.

12

Female pelvis

Basic anatomy (Figure 12.10)
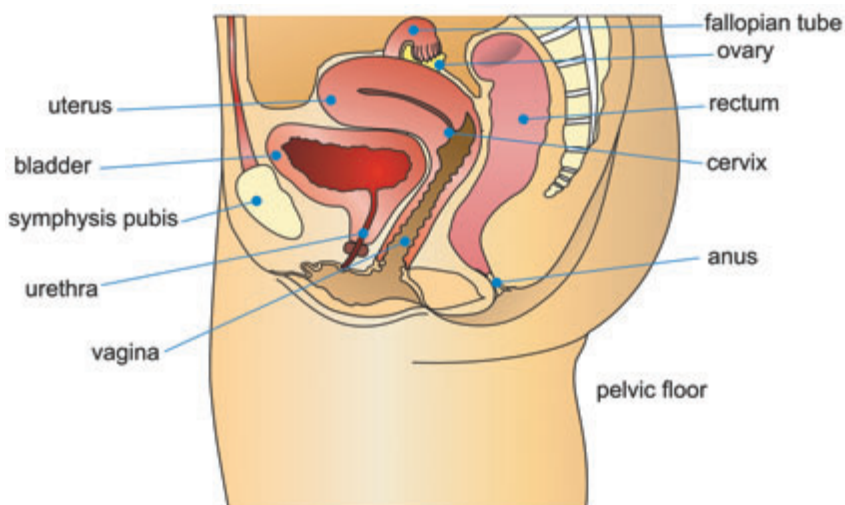
Figure 12.10 Sagittal section through the female pelvis showing midline structures.

Common indications

- Assessment of congenital abnormalities of the urogenital tract.
- Cervical lesions.
- Uterine lesions.
- Benign uterine tumours, e.g. leiomyoma and fibroids.
- Bladder lesions.
- Rectal lesions.
- Infertility.

Equipment

- Body coil/phased array pelvic coil/multi-array coil.
- Compression bands and foam immobilization pads if using the body coil.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch. Foam pads and compression bands can be applied across the patient's lower pelvis to reduce respiratory and bowel motion (unless the patient cannot tolerate this).

12

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the pubis symphysis and the iliac crest. If a local rectal coil is used, it should be carefully inserted prior to the examination. Ensure that it is correctly positioned and fully inflated.

Suggested protocol

Coronal breath-hold fast incoherent (spoiled) GRE/SE/FSE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gap are prescribed from the coccyx to the anterior aspect of the pubis symphysis. The area from the pubis symphysis to the iliac crests is included in the image.

P 60 mm to A 60 mm

Sagittal localizers are useful to confirm the correct positioning of a rectal coil and to evaluate the uterus.

L 25 mm to R 25 mm

Sagittal SE/FSE T2 (Figures 12.11 and 12.12)

Demonstrates organs that lie in the midline (bladder, uterus, rectum, cervix). Medium or thick slices/gap are prescribed from the left to the right pelvic side walls (see Figure 12.3). Unless lymph node involvement is suspected, small structures such as the cervix require high-resolution imaging using the rectal coil and thin slices/gap prescribed through the ROI only. Chemical/spectral presaturation pulses are often necessary when using FSE sequences.

Axial SE/FSE T2

Demonstrates organs that lie laterally (ovaries, lymph, nodes). Medium or thick slices/gap are prescribed from the pelvic floor to the iliac crests (see Figure 12.4). Unless lymph node involvement is suspected, small structures such as the cervix require high-resolution imaging using the rectal coil and thin slices/gap prescribed through the ROI only. Chemical/spectral presaturation pulses are often necessary when using FSE sequences.

Axial SE/FSE T1

Slice prescription as for Axial T2.

Coronal SE/FSE T2

Slice prescription as for Coronal SE/FSE T1.
   Chemical/spectral presaturation pulses are often necessary when using FSE sequences.

Figure 12.11 Sagittal FSE T2 weighted image through a female pelvis.

Figure 12.12 Sagittal FSE T2 weighted image demonstrating a large mass in the cervix. In this case the lesion has obstructed the endometrial cavity, causing distension.

12
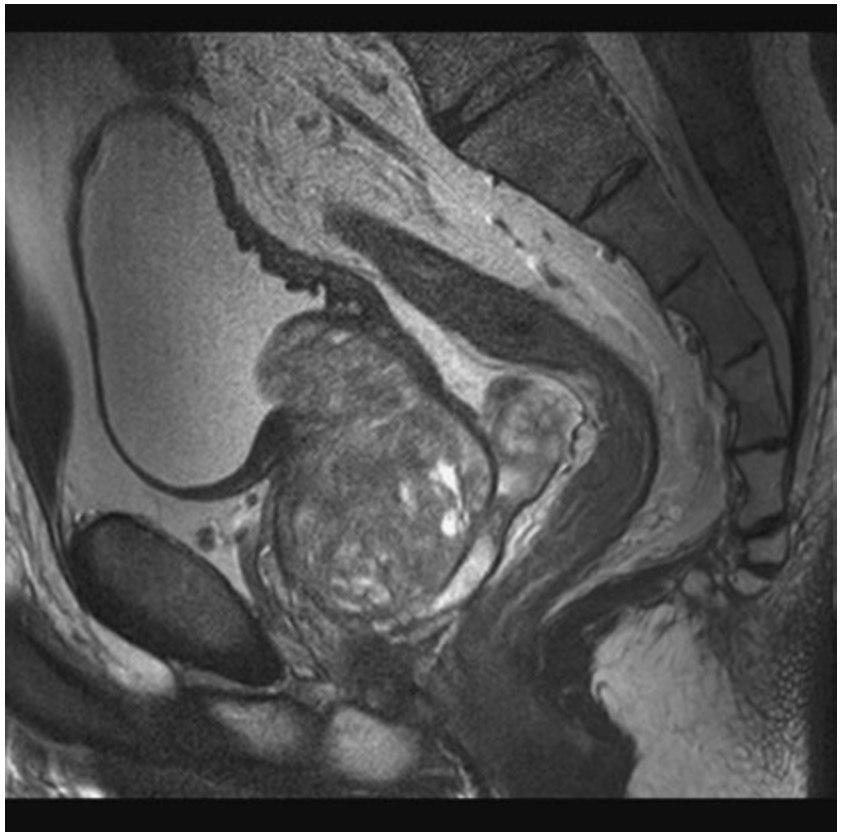
Additional sequences

SS-FSE/GRE-EPI/SE-EPI/diffusion imaging

Real-time imaging enables biopsies and laser ablations of lesions under MR control. In additional cine imaging of the uterus is useful to evaluate uterine contractility in a variety of disorders. In addition this technique may be used to evaluate the pelvic floor. DWI, which may be used in conjunction with parallel imaging techniques, may be used to differentiate malignant from benign lesions and to evaluate tumour response to therapy.

Image optimization

Technical issues

The pelvis offers excellent SNR and contrast, especially when phased array, multi-array or local rectal coils are used. As a result, spatial resolution is easily obtainable without compromising signal. In addition the use of parallel imaging techniques can significantly reduce scan times or increase resolution. FSE provides very good results in the pelvis, as respiration and bowel motion are less troublesome than in the abdomen. In addition, a rectangular/asymmetric FOV is routinely implemented with the long axis of the rectangle S to I in the sagittal images, and R to L in the axials. The combination of FSE, a rectangular/asymmetric FOV, and local or phased array coils (where a small FOV is implemented) enables the acquisition of very fine matrix sizes in conjunction with a short scan time. T2 weighting is optimal for evaluating the structure of the uterus.

On some systems, oversampling is not available with a rectangular/asymmetric FOV. If so, ensure that the FOV is large enough to incorporate all the pelvis, or apply spatial presaturation bands A and P to reduce aliasing. If SE is selected, a fine matrix may still be utilized to provide good spatial resolution and a fairly short scan time. Fat suppression techniques are often beneficial especially on FSE T2 images where fat and pathology return a similar signal.

12

Artefact problems

Bowel motion is reduced by compression and administering antispasmodic agents IV, IM or subcutaneously prior to the examination. Compression also reduces respiratory motion by encouraging the patient to breathe from their upper abdomen and chest, rather than their pelvis. Spatial presaturation pulses applied S and I to the FOV reduce flow motion artefact in the IVC, aorta and iliac vessels. GMN further reduces flow artefact but, as it increases signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. Additional shimming may be required before chemical/spectral presaturation sequences.

Patient considerations

Some patients may not be able to tolerate compression, especially if they have had recent abdominal surgery or have large lesions. Compression can also make a claustrophobic patient feel more trapped. Under these circumstances, placing the patient prone has the same (albeit lesser) effect as compression. In addition, if the ROI lies posteriorly (e.g. fistulae in the buttocks), placing the patient prone positions the ROI nearer to the magnetic isocentre, thereby increasing image quality. Some antispasmodic agents given IM may cause nausea, which can be alleviated by giving orange juice after the scan. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be given to enhance the conspicuity of certain lesions, especially in the cervix, uterus and ovaries. Dynamic imaging after contrast administration may improve tumour localization and staging and also help in monitoring response to therapy. Oral or rectal contrast agents including air (administered carefully) to label and demonstrate the rectum and lower gastrointestinal tract are sometimes useful.

12

Obstetrics

Common indications

- Evaluation of pelvic–cephalic disproportion in the second or third trimester of pregnancy, or post-delivery.
- Placenta praevia.
- Evaluation of pelvic disease incidental to pregnancy and foetal abnormalities (for foetal imaging see *Paediatric imaging*).

Equipment

- Body coil/multi-coil array.
- (Compression bands if tolerable post partum.)
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the pubis symphysis and the iliac crest. Compression should not be applied in pregnancy or immediately post-Caesarean section.

Suggested protocol

Sagittal SE T1

Medium slices/gap are prescribed on either side of the longitudinal alignment light to include the pubis symphysis and the sacrum. System software can be used to measure pelvic inlet and outlet dimensions.

L 15 mm to R 15 mm

Sagittal/Coronal/Axial SE/FSE/SS-FSE T1 and T2

As in standard protocol, for pelvic disease incidental to pregnancy and to evaluate foetal abnormalities.

Image optimization

Technical issues

MRI may be used to measure pelvic proportions, and to evaluate pelvic lesions incidental to pregnancy. The purpose of MRI pelvimetry is to

12

visualize the bony landmarks of the sacrum and the pubis symphysis so that accurate measurements can be made. Good SNR or spatial resolution is, therefore, usually unnecessary and, as these patients may have to be fitted into a busy schedule at short notice, scan time is the most important factor. If the coarsest matrix and lowest NEX/NSA are used, the above protocol takes only 1 or 2 minutes to acquire.

If examining the pelvis for foetal abnormalities or incidental pelvic disease, good resolution may be difficult to achieve due to foetal movement. Sedation of the foetus by injection of drugs via the umbilical vein may be used to still the foetus if clinically justified. Alternatively, fast sequences such as SS-FSE may be utilized very effectively. A rectangular/asymmetric FOV improves resolution, although the bulk of the abdomen in the AP axis may cause aliasing. The implementation of FSE and chemical/spectral presaturation techniques are not recommended in pregnant patients due to the increased RF deposition of these options. At present, it is still unclear whether large quantities of RF are damaging to the foetus.

Artefact problems

Foetal and bowel motion may interfere with the image, but not usually enough to obscure the bony landmarks necessary for pelvimetry measurements. Spatial presaturation pulses placed S and I to the FOV reduce flow in the aorta and IVC. Take great care if placing presaturation bands over the foetus as these increase the RF deposition within the infant. Minimizing the scan time is the best way of diminishing the effect of foetal movement in the image. Respiratory artefact is occasionally troublesome but RC is rarely necessary and breath-holding techniques can often be used.

Patient considerations

In most countries MRI is as yet not indicated in the first trimester of pregnancy as the possible risks are unknown. However, in the second and third trimesters MRI is often preferred to CT or other imaging modalities that use ionizing radiation. In the US, the FDA (Food and Drug Administration) approves the use of MR in all three trimesters if MR negates the use of more invasive testing. In the later stages of pregnancy, the patient may feel faint when lying in the supine position from the baby pressing on the IVC. Slightly raising one hip sometimes relieves this, but in pelvimetry studies it also complicates the calculation of the pelvic size as the patient is no longer truly sagittal. This is overcome by obliquing the sagittals from a localizer, but this lengthens the scan time due to the extra sequences involved. It is probably advisable to keep the patient supine and complete the scan as quickly as possible, rather than oblique her. Compression should not be used if the patient is pregnant or immediately post-Caesarean section. Due to excessively loud gradient noise associated

12

with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not usually given as the effect of the administration of contrast to pregnant and lactating patients has not yet been established.

13

Upper limb

13

Table 13.1 Summary of parameters. The figures given are general and should be adjusted according to the system used (Table 2.1)

Spin echo (SE)

short TE	min to 30 ms
long TE	70 ms +
short TR	300−600 ms
long TR	2000 ms +

Fast spin echo (FSE)

short TE	min–20 ms
long TE	90 ms +
short TR	400−600 ms
long TR	4000 ms +
short ETL	2−6
long ETL	16 +

Inversion recovery (IR) T1

short TE	min–20 ms
long TR	3000 ms +
medium TI	200−600 ms
short ETL	2−6

STIR

long TE	60 ms +
long TR	3000 ms +
short TI	100−175 ms
long ETL	12−20

FLAIR

long TE	60 ms +
long TR	3000 ms +
long TI	1700−2200 ms
long ETL	12−20

Coherent GRE

long TE	15 ms +
short TR	≤ 50 ms
flip angle	20°−40°

Incoherent GRE

short TE	min–5 ms
short TR	≤ 50 ms
flip angle	20°−40°

Balanced GRE

TE	minimum
TR	minimum
flip angle	≥ 40°

SSFP

TE	minimum
TR	40−50 ms
flip angle	20°−40°

Slice thickness

2D	thin	2−4 mm
	medium	5−6 mm
	thick	8 mm
3D	thin	≤ 1 mm
	thick	≥ 3 mm

Slice numbers

Volumes	small	≤ 32
	medium	64
	large	≥ 128

Matrix (frequency × phase)

coarse	256 × 128 or 256 × 192
medium	256 × 256 or 512 × 256
fine	512 × 512
very fine	≥ 512 × 512

FOV

small	≤ 18 cm
medium	18−30 cm
large	≥ 30 cm

PC-MRA

2D and 3D	TE	minimum
	TR	25−33 ms
	flip angle	30°
VENC venous		20−40 cm/s
VENC arterial		60 cm/s

NEX/NSA

short	≤ 1
medium	2−3
multiple	≥ 4

TOF-MRA

2D	TE	minimum
	TR	28−45 ms
	flip angle	40°−60°
3D	TE	minimum
	TR	25−50 ms
	flip angle	20°−30°

13

Shoulder

Basic anatomy (Figure 13.1)

Figure 13.1 Coronal/oblique view of the right shoulder showing bony structures and main ligaments.

Common indications

- Evaluation of shoulder pain.
- Diagnosis of impingement syndrome.
- Suspected rotator cuff tear.
- Evaluation of recurrent dislocation (instability).
- Frozen shoulder syndrome.

Equipment

- Shoulder array/small surface coil pair or multi-array/small flexible coil.
- Immobilization pads and straps.
- Ear plugs.

Patient positioning

The patient lies supine with the arms resting comfortably by the side. Slide the patient across the table to bring the shoulder under examination as

close as possible to the centre of the bore. Relax the shoulder to remove any upward 'hunching'. The arm to be examined is strapped to the patient, with the thumb up (neutral position) and padded so that the humerus is horizontal. Place the coil to cover the humeral head and the anatomy superior and medial to it. If a surface or flexible coil is used, care must be taken to ensure that the flat surface of the coil is parallel to the Z axis when it is placed over the humeral head (Figure 1.1). Centre the FOV on the middle of the glenohumeral joint. Patient and coil immobilization are essential for a good result. Instruct the patient not to move the hand during sequences. The patient is positioned so that the longitudinal alignment light and the horizontal alignment light pass through the shoulder joint.

Suggested protocol

Axial/Coronal incoherent (spoiled) GRE/SE/FSE T1

Acts as a localizer if three-plane localization is unavailable and ensures that there is adequate signal return from the whole joint. Medium slices/gap are prescribed relative to the horizontal alignment light so that the supraspinatus muscle is included in the image.

Axial localizer: I 0 mm to S 25 mm

Axial SE/FSE T2 or coherent GRE T2* (Figure 13.2)

Thin slices/gap are prescribed from the top of the acromioclavicular joint to below the inferior edge of the glenoid (Figure 13.3). The bicipital groove on the lateral aspect of the humerus to the distal supraspinatus muscle is included in the image. The axial projection displays joint cartilage and glenoid labrum, intra-osseous changes associated with Hills–Sachs deformity, and the condition of muscles and tendons of the rotator cuff.

Coronal/oblique SE/FSE T1 (Figure 13.4)

Thin slices/gap are prescribed from the infraspinatus posteriorly to the supraspinatus anteriorly and angled parallel to the supraspinatus muscle (Figures 13.5 and 13.6). This is best seen on a superior axial view, but coverage is easier to assess on an axial image through the lower third of the humeral head. The superior edge of the acromion to the inferior aspect of the subscapularis muscle (about 1 cm below the lower edge of the glenoid), and the deltoid muscle laterally, and the distal third of the supraspinatus muscle medially are included on the image.

Coronal/oblique SE/FSE T2 +/– chemical/spectral presaturation (Figures 13.7 and 13.8)

Slice prescription as for Coronal/oblique T1.

13

Figure 13.2 Axial GRE T2* weighted image of the shoulder showing normal appearances.
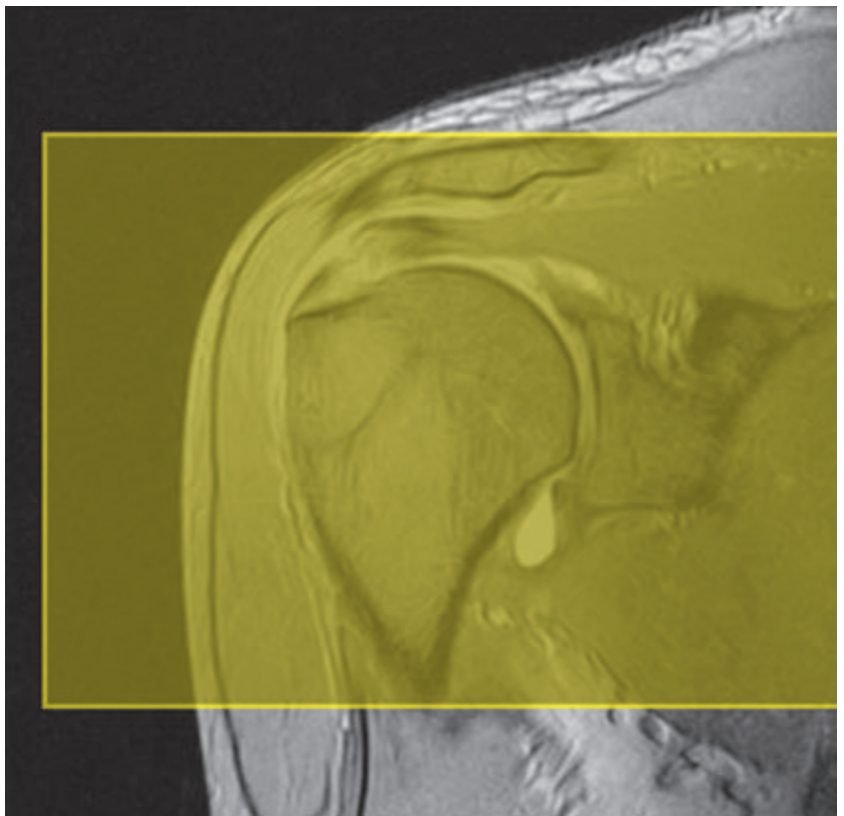
Figure 13.3 Axial GRE T2* weighted image showing slice prescription boundaries and orientation for axial imaging of the shoulder.

Figure 13.4 Coronal/oblique T1 weighted FSE through the shoulder.
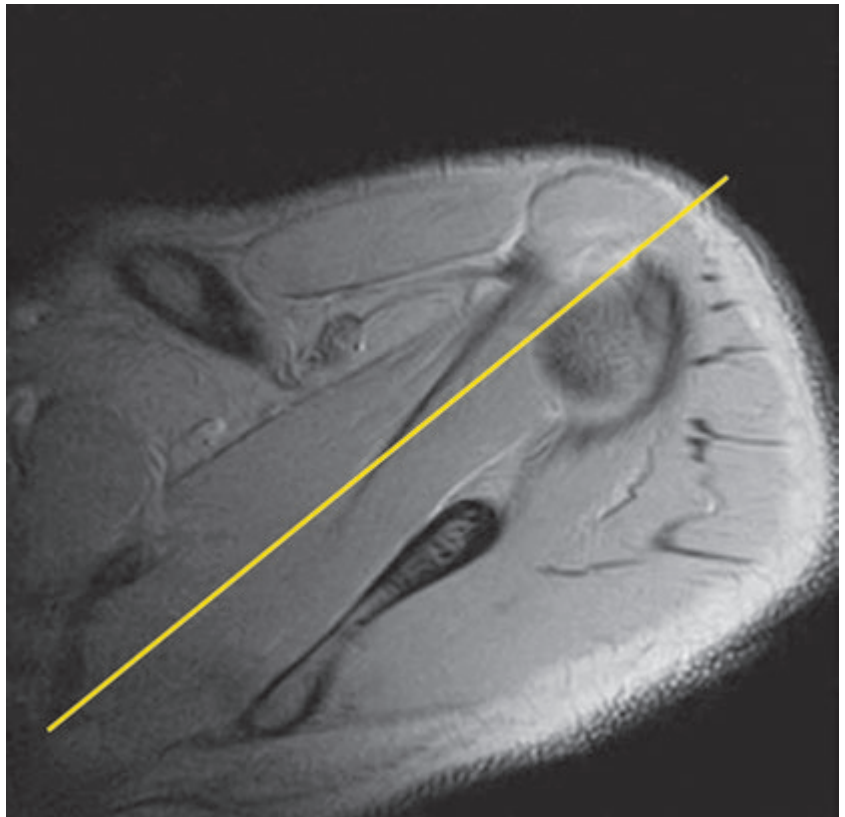
Figure 13.5 Axial SE T1 weighted localizer of the shoulder showing the angle of the supraspinatus muscle.
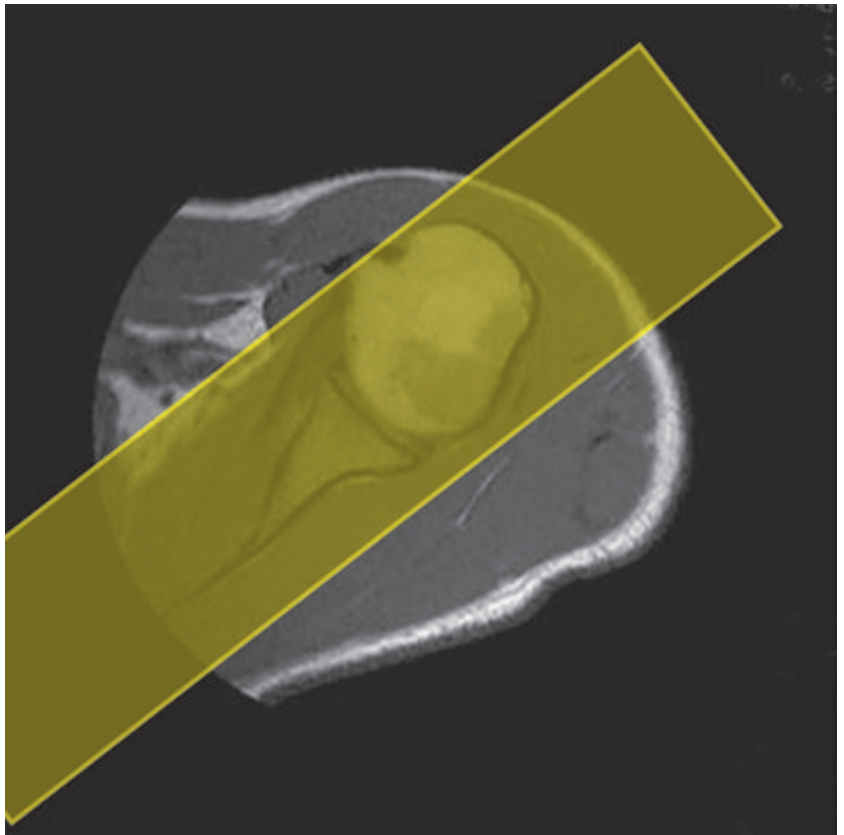
Figure 13.6 Coronal/oblique T1 weighted image showing slice prescription boundaries and orientation for axial imaging of the shoulder.

Figure 13.7 Coronal/oblique FSE T2 weighted image with chemical/spectral presaturation.

Figure 13.8 Coronal/oblique FSE T2 weighted image.

Fat suppressed T2 weighted images clearly display muscle tears, trabecular injury, joint fluid and tendon tears. If SE is used chemical/spectral presaturation may not be necessary.

Additional sequences

Sagittal/oblique SE/FSE T1

As for Coronal/oblique T1, **except** slices are prescribed from medial to the glenoid cavity to the bicipital groove laterally. The area from the distal portion of the joint capsule to the superior border of the acromion is included in the image (Figure 13.9).

Sagittal/oblique/Axial FSE PD/T2 +/– chemical/spectral presaturation

This sequence provides a combination of anatomical display, tendon assessment, display of joint cartilage and sensitivity to trabecular damage.

13
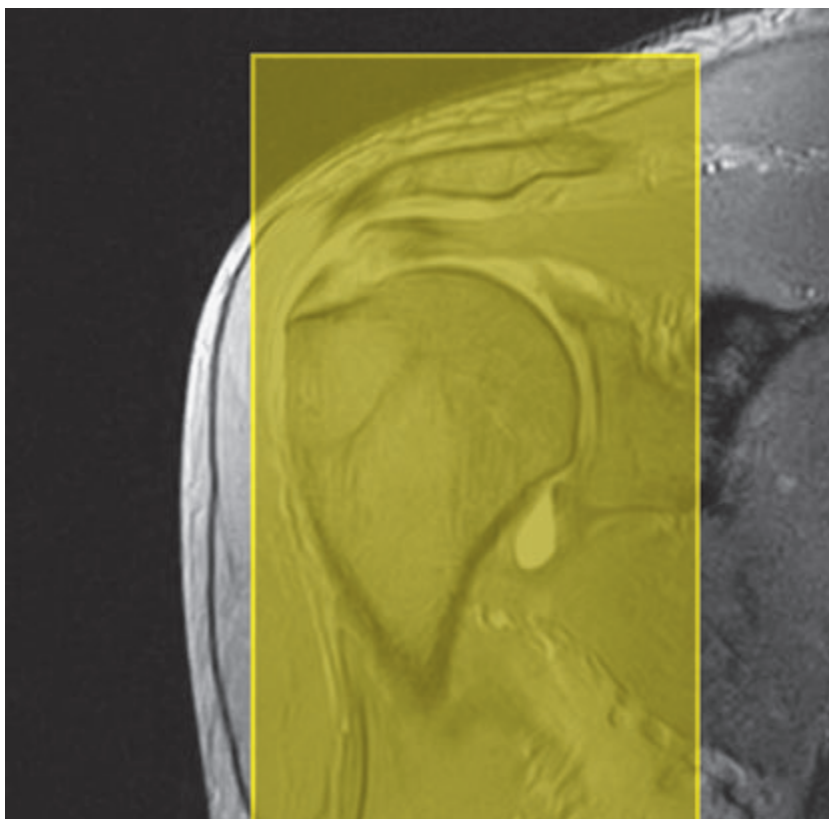
Figure 13.9 Coronal/oblique GRET2 weighted image showing slice prescription boundaries and orientation for sagittal imaging of the shoulder.

MR arthrography (Figures 13.10 and 13.11)

The intra-articular use of gadolinium (MR arthrography) is used to diagnose rotator cuff tears, glenoid labral disruption and chondral defects. The technique usually involves injecting a very dilute solution of contrast in saline (1 : 100) or a very weak concentration of gadolinium into the joint capsule under fluoroscopic control followed by conventional MR imaging. Alternatively, saline injection followed by fat suppressed T2 weighted FSE sequences, or examining the joint after prolonged exercise to exacerbate a joint effusion, may be effective.

Image optimization

Technical issues

The SNR of the shoulder is largely dependent on the quality and type of coil used. Dedicated shoulder coils return a much higher and more uniform signal than a surface coil, and therefore the technique is adapted

13

Figure 13.10 Sagittal T1 weighted arthrogram.

13
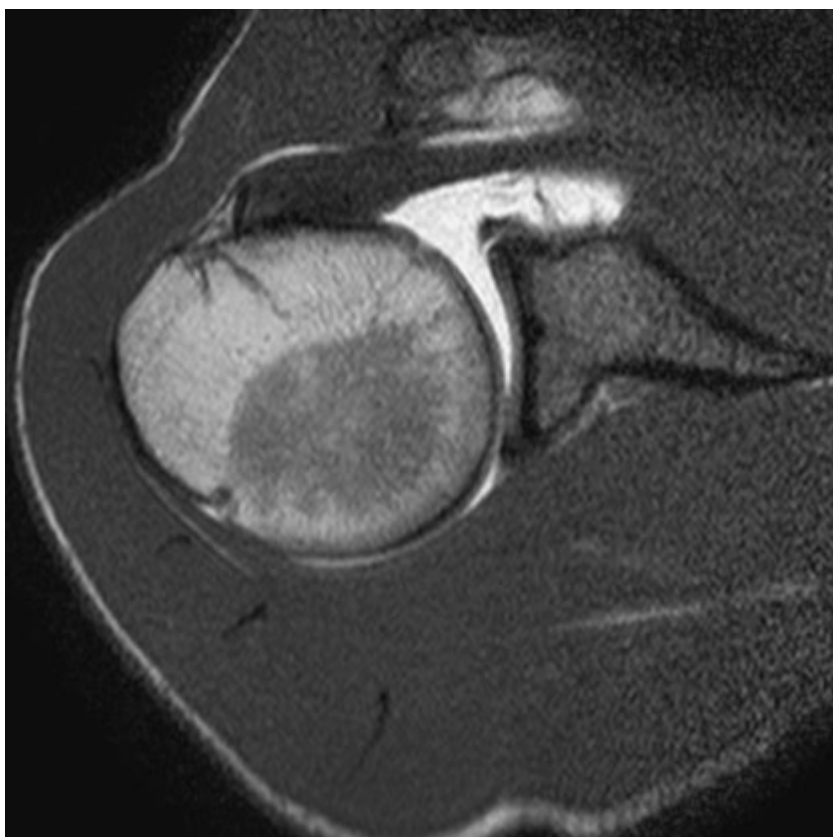
Figure 13.11 Axial T1 weighted arthrogram.

accordingly. If using a dedicated coil, thinner slices and finer matrices can be used to achieve the necessary spatial resolution without unduly lengthening the scan time. If the coil is poor, some resolution may have to be sacrificed in order to maintain the SNR and keep the scan time within reasonable limits. However, spatial resolution is the key to accuracy in shoulder imaging and the resolution must not drop below 0.8 mm. SE and FSE are usually the sequences of choice but coherent GRE and STIR are useful to visualize joint fluid. STIR may provide better results than fat suppressed FSE if magnet shimming is suboptimal.

Artefact problems

The main sources of artefact are patient movement and flow motion from the subclavian vessels. Spatial presaturation pulses placed I and medial to the shoulder under investigation are usually very effective at reducing phase ghosting. GMN also minimizes flow artefact but, as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. However, GMN effectively increases the contrast of synovial fluid in T2 and T2* weighted images. Additional shimming may be required before chemical/spectral presaturation sequences.

Respiration is sometimes troublesome. In coronal/oblique and axial imaging, the FOV is offset so that the centre of the shoulder is in the centre of the image. When using high degrees of obliquity some systems automatically swap the direction of phase and frequency encoding axes, which can cause severe aliasing problems unless oversampling is utilized. At angles beyond 45°, some systems may consider a coronal/oblique as a sagittal/oblique, altering the presented orientation and the anatomical markers (a right shoulder could look like a left). The same problems can arise in sagittal/oblique imaging. To avoid problems, check the direction of phase encoding for every oblique scan prescription and use anatomical markers in sagittal/oblique images to confirm the scanner's labelling of anterior and posterior. To minimize aliasing, phase encoding should run A–P on axials and sagittal/obliques, and S–I on the coronal/obliques. Alternatively, spatial presaturation pulses can be positioned to minimize artefact from the medial edges of the coil.

A phenomenon known as the 'magic angle' causes increased signal intensity in tendons in short TE sequences when tendons are orientated at an angle of 55° to the main field. Normally tendons produce little or no signal on conventional MRI sequences because tendons consist of parallel ordered bundles of collagen fibres. This structural anisotropy causes a local static magnetic field which, when superimposed on to the static field, increases spin–spin interactions and therefore shortens T2 relaxation rates so much that the tendon has a low signal intensity.

However, the rate at which spin dephasing is increased is proportional to the angle between the main field and the long axis of the tendon. Because of this relationship, additional spin dephasing caused by the structural anisotropy of tendons decreases to zero when this angle is 55°.

13

Therefore at this angle the T2 relaxation time increases, causing a high signal intensity when using short TEs. The increased signal can mimic pathology such as tendonitis in normal tendons. It is seen in many tendons especially supraspinatus and Achilles tendons as well as in the wrist. The magic angle effect can be eliminated by repositioning the tendon or by increasing the TE above a critical value.

Patient considerations

Ensure that the patient is comfortable and well informed of the procedure. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely used in shoulder imaging except for direct and indirect MR arthrography. For information on direct MR arthrography please see previous section under *Additional sequences*. Indirect MR arthrography involves the administration of intravenous diluted gadolinium and is sometimes used when direct arthrography is not feasible. Although indirect MR arthrography has some disadvantages when compared with direct MR arthrography, it does not require fluoroscopic guidance or invasive joint injection. It is also superior to non contrast MR imaging in delineating structures when there is minimal joint fluid. In addition, vascularized or inflamed tissue enhances with this method.

13

Humerus

Basic anatomy (Figure 13.12)
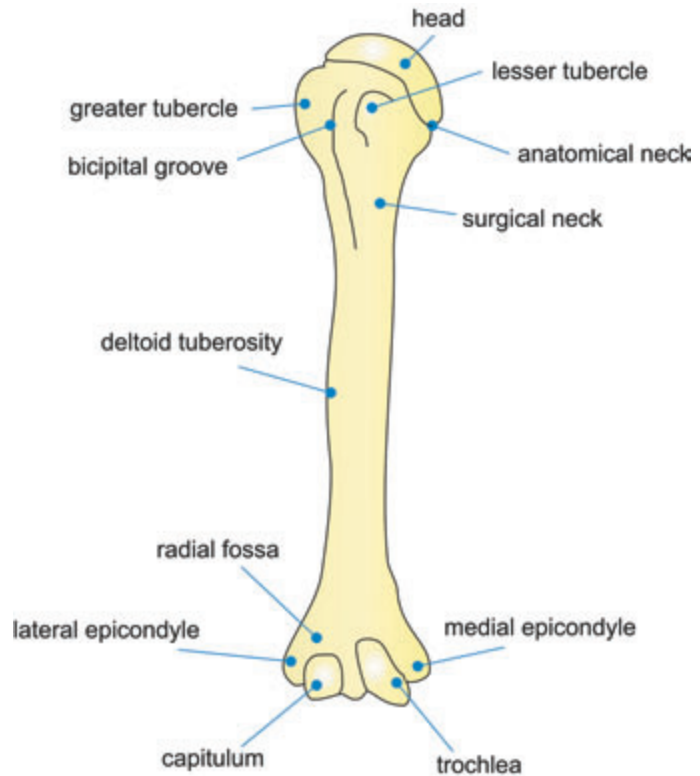
Figure 13.12   Anterior view of the right humerus.

Common indications

- Diagnosis and assessment of bony and soft tissue abnormalities (mass lesions, muscle tears, deformity).
- A single-sided examination is usually preferred as bilateral examinations severely compromise resolution.

Equipment

- Body multi-array coil/long surface coil placed under the humerus.
- Immobilization pads and straps.
- Plastic ruler.
- Ear plugs.

13

Patient positioning

If the upper arm is under investigation, the patient lies supine on the examination couch with their arms resting at their sides. If, however, the ROI is near the elbow, the patient may lie prone with their arm stretched above their head (swimmer's position). This ensures that the area under examination is at isocentre and offset imaging is avoided. However, the swimmer's position can be difficult to maintain for long periods of time and it is therefore advisable to reserve it for fitter patients. In both positions it is necessary to place the coil lengthwise along the long axis of the humerus.

When imaging with the arm at the side, raise the unaffected side about 45° and bring the arm under examination as close as possible to the longitudinal alignment light. The top half of the body array should be positioned with its lateral edge wrapped well around the arm and touching the lower element edge. This avoids placing the arm at the coil edge. Additionally, for full humerus imaging, the top half of the array is slid up to cover the shoulder, while the base portion is used to image from the elbow up. Use immobilization straps to secure the coil, the patient, and supporting pillows.

If the patient is in the swimmer's position, the longitudinal alignment light lies along the midline of the humerus. In both positions, the horizontal alignment light passes through the centre of the coil or midway between the shoulder and the elbow. The arm and coil may be raised with foam pads until the vertical alignment light lies through the centre of the arm, so avoiding a vertical offset. Use the plastic ruler to measure from the transverse alignment light to the joints to ensure the full length of the arm fits within the long axis of the FOV. If not, include either the shoulder or elbow depending on the location of the lesions. When a lesion is palpable place an oil- or water-filled marker over it. For large lumps or scars place a marker at each end.

Suggested protocol

Coronal/Sagittal incoherent (spoiled) SE/FSE T1

Acts as a localizer if three-plane localization is unavailable but, if the patient has been positioned correctly, it may act as a diagnostic sequence. Coronal localizers should be used for lesions located in the RL axis, sagittal localizers for lesions in the AP axis.

Coronal imaging: Medium slices/gap are prescribed on either side of the vertical alignment light and offset to the middle of the humerus (if the arm is at the side). No offset is necessary in the swimmer's position as the longitudinal alignment light corresponds to the middle of the humerus. The whole of the humerus, from the elbow to the shoulder, is included in the image.

P 25 mm to A 25 mm

13

Sagittal imaging: Medium slices/gap are prescribed on either side of the longitudinal light in the swimmer's position, or on either side of the offset measurement when imaging with the arms at the side. The whole of the humerus, from the elbow to the shoulder, is included in the image.

<div align="right">

L 25 mm to R 25 mm
(swimmer's position)

</div>

Sagittal STIR

Medium slices/gap are prescribed to cover the whole of the humerus from the glenoid to the proximal radius and ulna, and orientated along the long axis of the humerus. This sequence is useful to identify lesions in the soft tissues and marrow space and display their extent.

Coronal FSE/SE T1

Thin slices/gap are prescribed to cover the humerus from back to front and orientated along the long axis of the humerus. This sequence provides an anatomical display of the upper arm and may identify lesions located in the marrow space.

Axial SE/FSE T1

Medium slices/gap are prescribed and positioned to include lesions seen on the coronal or sagittal images. Axial images are used to localize lesions within significant anatomical compartments and must extend well above and below the lesions. Breach of the marrow space, extension within or through muscle compartments and association with the neurovascular bundle are all significant characteristics.

Axial FSE T2 chemical/spectral presaturation/STIR

Slice prescription as for Axial T1.

STIR sequences are usually needed if the arm is by the side or if the ROI is away from the longitudinal isocentre. Chemical/spectral presaturation is more effective in the swimmer's position when the ROI is at isocentre.

Image optimization

13

Technical issues

The inherent contrast is relatively good in this area due to the apposition of muscle and fat. Medium slice thickness and resolution, combined with sensitive coils, permit a fast examination so that higher-resolution axial images can be acquired when lesions are close to the neurovascular bundle, or cortical bone breach is not obvious.

The FOV is usually extended on the coronals and sagittals so that the entire length of the humerus is visualized. This is especially important in the diagnosis of bony tumours to ensure that any additional skip lesions are identified. The associated scan time reductions of FSE enable the implementation of medium to fine matrices, without unduly lengthening the scan time. In the coronal and sagittal planes, a rectangular/asymmetric FOV is beneficial to maintain resolution with the long axis of the rectangle placed S to I. In coronal imaging an offset square FOV or oversampling is required to avoid aliasing, especially when using a large coil.

When using FSE with T2 weighting, the muscles return a lower signal than in SE and fat returns a higher signal (*see Pulse sequences* in Part 1). Chemical/spectral presaturation techniques are, therefore, usually necessary to distinguish fat from pathology. Multiple NEX/NSA are required to compensate for this or, alternatively, the coil can be placed anteriorly over the arm.

Artefact problems

Patient movement is sometimes troublesome in the swimmer's position as the patient is more likely to be uncomfortable. Careful immobilization or laying the patient supine instead is beneficial. Pulsation from the humeral vessels is reduced by using spatial presaturation pulses placed S and I to the FOV and I on axial imaging. Medial spatial presaturation pulses also reduce aliasing. GMN can be implemented but, as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. Chemical shift artefact must be kept within one pixel, particularly in axial imaging, to delineate the interface of marrow and cortical bone and the edges of muscle compartments clearly. Additional shimming may be required before chemical/spectral presaturation sequences.

Patient considerations

Patients must be carefully positioned if the swimmer's position is used and immobilized with foam pads for comfort. To allow accurate assessment of mass lesions, MRI should be performed before biopsy. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be useful for visualizing some soft tissue abnormalities but it is not routinely used.

13

Elbow

Basic anatomy (Figures 13.13 and 13.14)
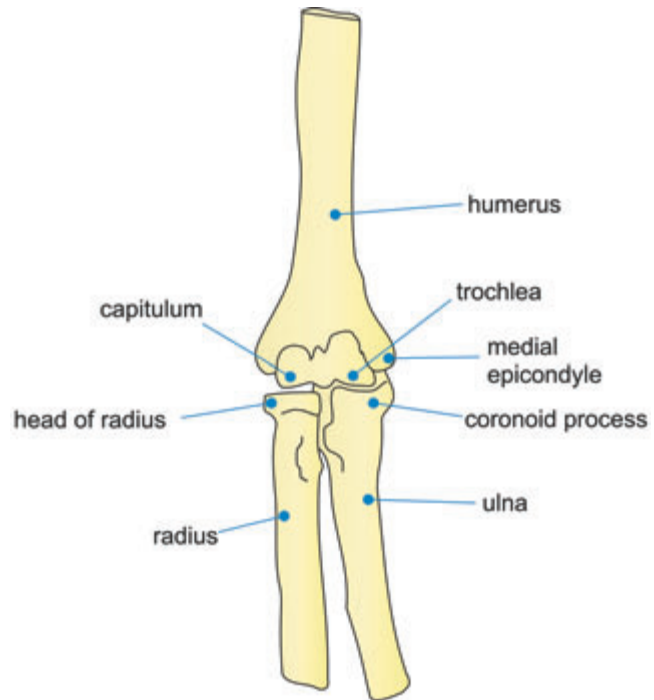
Figure 13.13 Anterior view of the right elbow showing the bony components.

Common indications

- Osteochondral defects and loose bodies.
- Ulnar nerve compression.
- Trauma, particularly ulnar collateral ligament injury.
- Soft tissue mass lesions.
- Muscle tear and rupture.

13

Equipment

- Small surface coils combined as an array/Helmholtz pair/flexible coils/surface coil fixed anteriorly to the joint.
- Immobilization pads and straps.
- Plastic elbow slabs.
- Ear plugs.
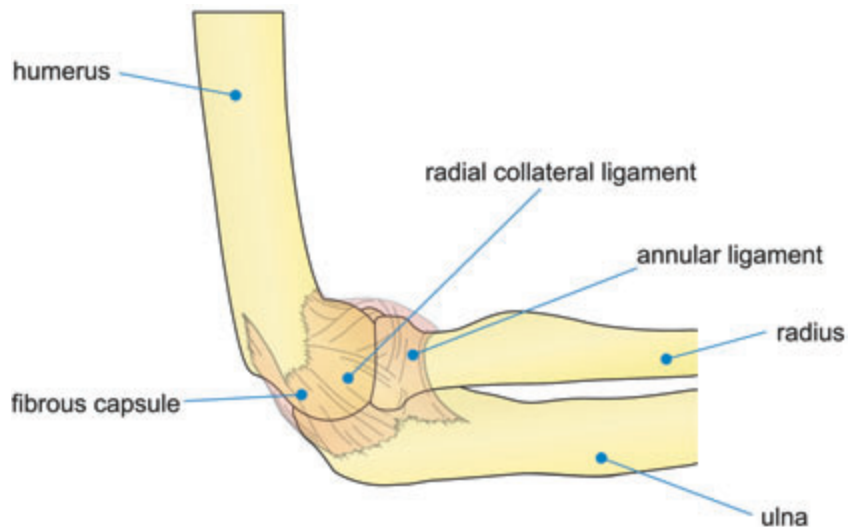
Figure 13.14   Sagittal view of the right elbow showing ligaments on the lateral aspect.

Patient positioning

The patient lies either supine with their arm at the side, or prone in the swimmer's position with the elbow under examination extended above the head and the other arm down by the side. While this ensures that the area under examination is at isocentre it is difficult to maintain for long periods of time, and it is therefore advisable to reserve it for fitter patients.

With the more common supine position, the body is obliqued and drawn across the table to place the elbow as close as possible to the midline whilst lying clear of the body. The elbow and wrist are secured in a relaxed position. Plastic back slabs and/or rigid coils help to maintain the position and reduce muscular motion. The arm and coil are raised using foam pads so that the vertical alignment light lies through the centre of the joint, so avoiding a vertical offset. The longitudinal alignment light lies between the humeral condyles.

Suggested protocol

Coronal/multiplanar incoherent (spoiled) GRE/SE/FSE T1

Acts as a localizer if three-plane localization is unavailable but, if the patient is positioned correctly, it may act as a diagnostic sequence. All main imaging scan planes are aligned to the anatomical axes of the elbow. As the elbow is in a relaxed oblique position, fast localizers can be used to find and establish these planes. Fast, low-resolution localizers can also be set up with small FOVs to rapidly assess the need for anti-aliasing options. Thin slices/gap are prescribed on either side of the vertical alignment light

or with an offset if the arms are at the side. The whole of the elbow joint is included in the image.

Coronal localizer: P 20 mm to A 20 mm

Coronal SE/FSE T1 (Figure 13.15)

Thin slices/gap are prescribed through a line joining the humeral epicondyles from the posterior to the anterior skin surfaces. The distal humerus, elbow joint and proximal radius and ulna, including the lateral and medial skin margins, are included on the image.

Coronal FSE PD/T2 +/– chemical/spectral presaturation/ STIR (Figures 13.16 and 13.17)

Slice prescription as for Coronal T1, **except** use chemical/spectral presaturation for identification of occult fractures and joint degeneration.

Sagittal SE/FSE T1

Thin slices/gap are prescribed perpendicular to the coronal slices from the medial to the lateral aspects of the elbow (Figure 13.18). This sequence is used to evaluate lesions anterior or posterior to the bony anatomy and assess the long axis of associated muscles and tendons.

Sagittal STIR (Figure 13.19)

Slice prescription as for Sagittal T1.

Axial FSE T1 or PD/T2 +/– chemical/spectral presaturation (Figure 13.21)

Thin slices/gap are aligned perpendicular to the long axis of the humerus and forearm, as determined from a coronal view (Figure 13.20). These slices are typically oblique, with the medial edge more inferior than the lateral edge.

Coherent GRE T2* +/– chemical/spectral presaturation

These images display articular cartilage clearly for clarifying osteochondral defects.

13

Additional sequences

Incoherent (spoiled) GRE T1

Reduced signal intensity in the marrow space due to susceptibility effects, combined with high signal from muscle, makes this sequence useful in examining elbow joint anatomy.

Figure 13.15 Coronal SE T1 weighted image of the elbow showing normal appearances.

13

Figure 13.16 Coronal FSE T2 weighted image of the elbow with chemical/spectral presaturation showing normal appearances.
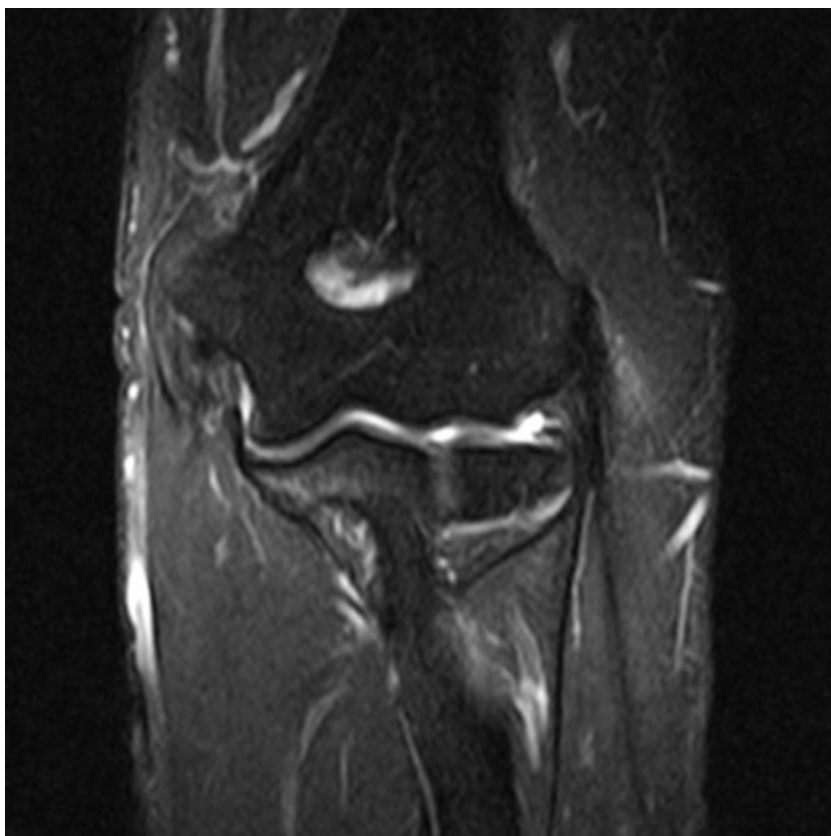
Figure 13.17 Coronal STIR.
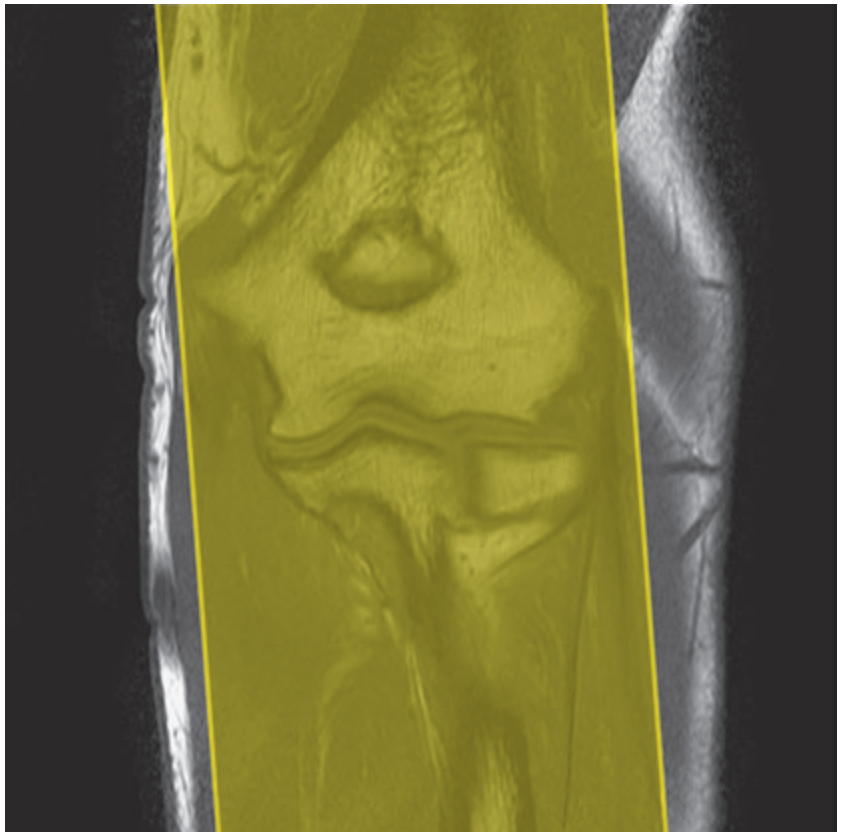
Figure 13.18 Coronal SE T1 weighted image of the elbow showing slice prescription boundaries and orientation for sagittal imaging of the elbow.

13
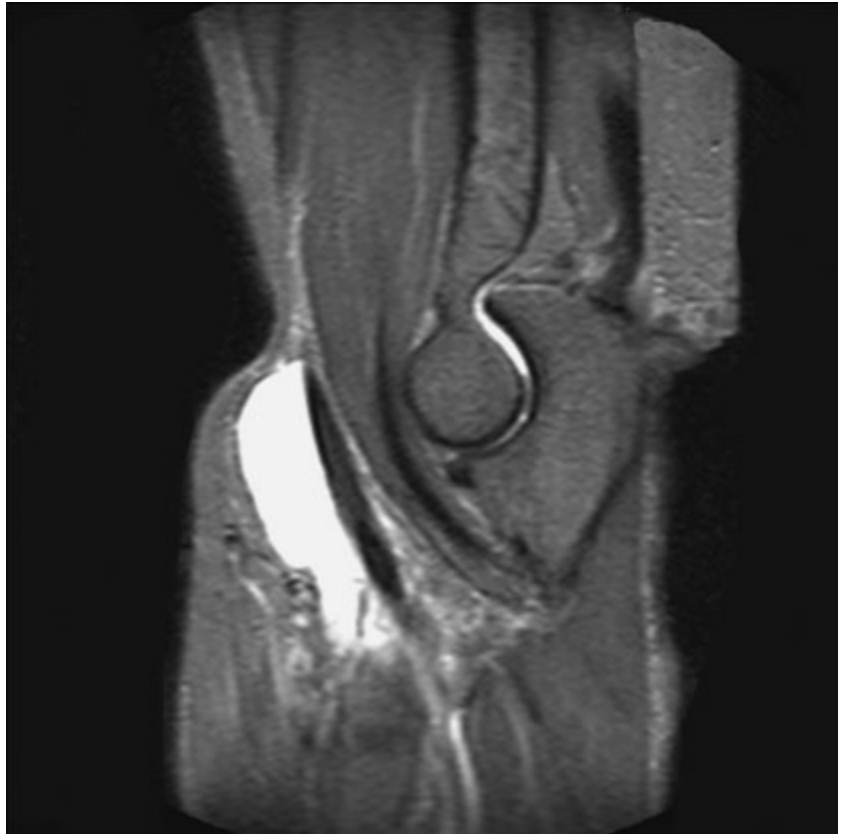
Figure 13.19 Sagittal STIR.

Coronal 3D coherent GRE PD/T2*

Thin slices and a small number of slice locations are prescribed through the joint allowing for slice wrap. The use of an isotropic dataset provides further evaluation of the elbow joint.

Image optimization

Technical issues

High-resolution imaging is required to demonstrate the elbow joint and therefore image quality is mainly dependent on the quality of the coil used. If a coil pair or array is implemented, the necessary spatial resolution can be easily maintained. In most cases the FOV is close to the periphery of the magnet bore and, therefore, extra shimming may be required to maximize SNR and image quality. FSE is commonly used to maintain high resolution in acceptable scan times. FSE also provides good contrast, but when used with T2 weighting the muscles return a lower signal than in SE and fat remains bright (*see Pulse sequences* in Part 1). Chemical/spectral presaturation is, therefore, often necessary to

13
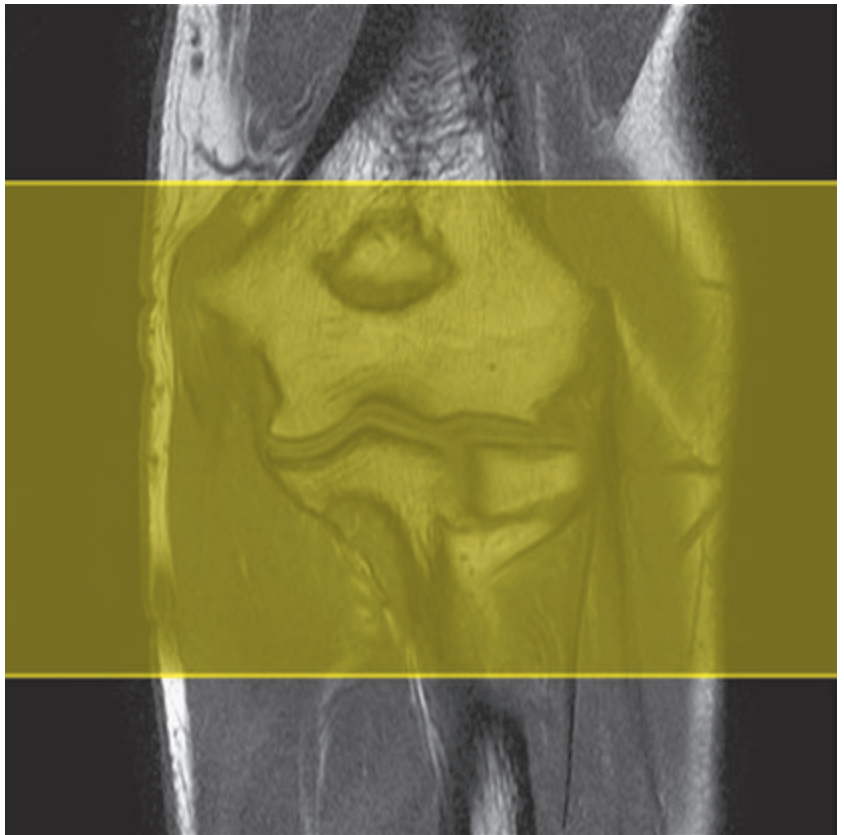
Figure 13.20 Coronal SE T1 weighted image of the elbow showing slice prescription boundaries and orientation for axial imaging of the elbow.

13
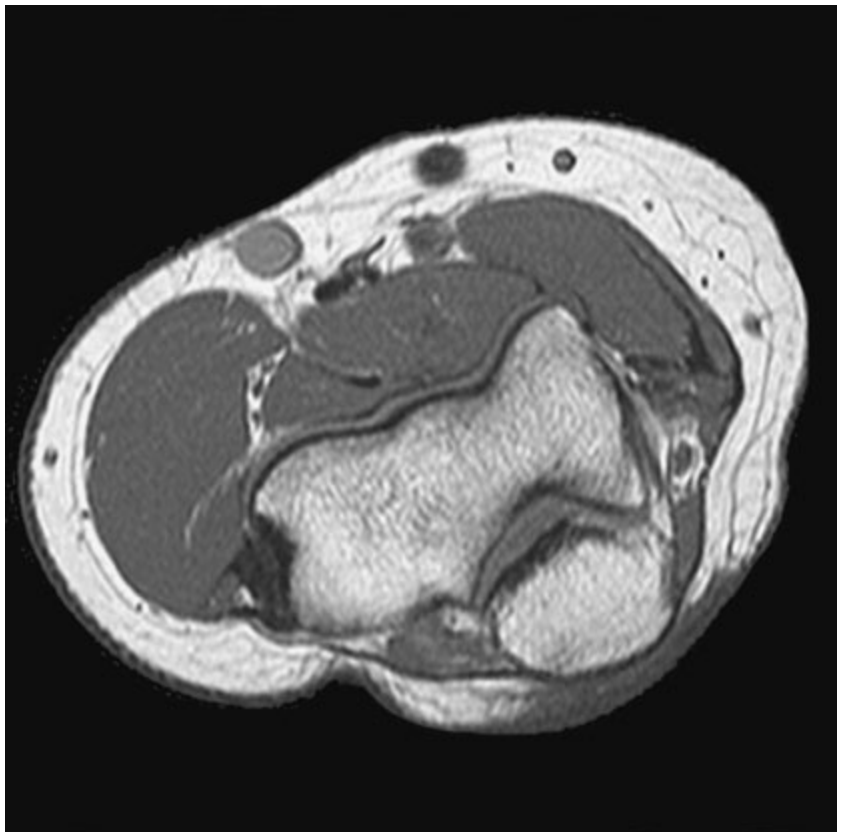
Figure 13.21 Axial FSE T1 weighted image through the elbow joint.

distinguish fat from pathology. Coherent GRE sequences are also used as they provide good contrast between the bony margins of the joint and synovial fluid. Volume acquisitions are sometimes valuable as very thin slices with no gap are used, and joint structures may be visualized in any plane.

Artefact problems

Patient movement can be troublesome in the swimmer's position as the patient is more likely to be uncomfortable. Careful immobilization, or laying the patient supine instead, is beneficial. Pulsation from the humeral and radial vessels is reduced using spatial presaturation pulses placed S and I to the FOV. GMN can also be used but, as it increases signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. However, GMN effectively increases the contrast of synovial fluid in T2 and T2* weighted images. If offset imaging is employed and phase is S to I, oversampling is necessary on the coronals. In axial imaging there is no anatomy outside the FOV in the phase direction, and in sagittal imaging there is no offset. Therefore oversampling is usually unnecessary in these planes. Additional shimming may be required before chemical/spectral presaturation sequences.

Patient considerations

Patients must be carefully positioned if the swimmer's position is used and immobilized with pads for comfort. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be useful for visualizing some soft tissue abnormalities. In addition, MR arthrography is useful for visualizing partial- and full-thickness tears of the collateral ligament and delineating bands in the elbow.

Forearm

Basic anatomy (Figure 13.22)
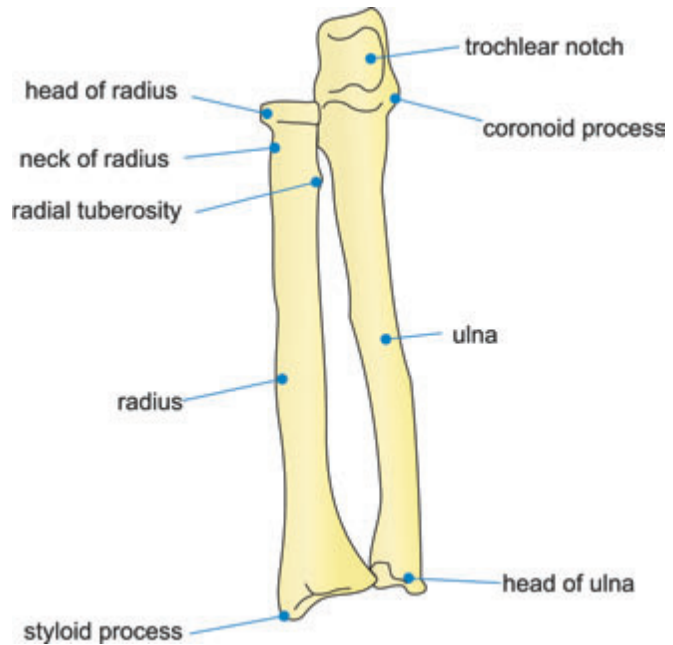
Figure 13.22 Anterior view of the right radius and ulna.

Common indications

- Visualization of bony and soft tissue abnormalities.

Equipment

- Body array coil/long surface coil placed under the arm/extremity coil for focal lesions/body coil.
- Immobilization pads and straps.
- Plastic ruler.
- Ear plugs.

Patient positioning

The patient may lie either supine with the arms at the side, or prone in the swimmer's position with the arm under investigation above the head and

13

the other arm down by the side. This ensures that the area under examination is at isocentre and offset imaging is avoided. However, this position is difficult to maintain for long periods of time and it is therefore advisable to reserve it for fit patients.

When imaging with the arm at the side, raise the unaffected side about 45° and bring the arm under examination as close as possible to the centre of the bore. The top half of the body array should be positioned with its lateral edge wrapped well around the arm and touching the lower element edge. This avoids using the edge of the coil. In addition, when imaging the whole of the forearm, the top half of the array is slid up to cover the elbow, while the base portion is used to image from the wrist up. While keeping the arm relaxed it is important to avoid pronation of the hand. Use immobilization straps to secure the coil, patient, and supporting pillows or pads. Instruct the patient not to move their fingers during data acquisition.

In both positions, the horizontal alignment light passes through the centre of the coil or midway between the elbow and the wrist. The arm and coil may be raised with foam pads until the vertical alignment light lies through the centre of the arm, so avoiding a vertical offset. Use the plastic ruler to measure from the horizontal alignment mark to each joint. This ensures that the full length of the forearm fits within the FOV. If this is not possible include either the elbow or the wrist depending on the location of the lesions. When a lesion is palpable place an oil- or water-filled marker over it. For large lumps or scars place a marker at each end.

Suggested protocol

Multiplanar/Coronal/Sagittal incoherent (spoiled) GRE/SE/FSE T1

Acts as a localizer if three-plane localization is unavailable but, if the patient has been positioned correctly, may act as a diagnostic sequence. Coronal localizers should be used for lesions located in the RL axis, sagittal localizers for lesions in the AP axis. Surface coil localizers can be used to quickly assess potential aliasing problems and for establishing anatomical planes.

Coronal imaging: Medium slices/gap are prescribed on either side of the vertical alignment light and offset to the middle of the forearm (if the arm is at the side). No offset is necessary in the swimmer's position as the longitudinal alignment light corresponds to the middle of the forearm. The whole of the forearm from the wrist to the elbow is included in the image.

P 25 mm to A 25 mm

Sagittal imaging: Medium slices/gap are prescribed on either side of the longitudinal light in the swimmer's position or on either side of the offset

measurement when imaging with the arms at the side. The whole of the forearm from the wrist to the elbow is included in the image.

**L 25 mm to R 25 mm
(swimmer's position)**

Sagittal STIR

Medium slices/gap are prescribed to include the whole forearm from the distal humerus to the proximal metacarpals and orientated along the long axis of the humerus accounting for the 'carry angle' of the forearm. This sequence is fast and sensitive for identifying lesions in the soft tissues and marrow space.

Coronal FSE/SE T1

Thin slices/gap are prescribed along the line of the forearm and from the posterior to the anterior skin surfaces.

Axial T1 FSE

Medium slices/gap are prescribed perpendicular to the coronal slices to extend well above and below lesions seen in this, and the sagittal plane. Breach of the marrow space, extension within or through muscle compartments, and association with the neurovascular bundle are all significant characteristics best assessed on axial images.

Axial FSE T2 +/− chemical/spectral presaturation or STIR

Slice prescription as for Axial T1.

STIR sequences are usually required if the arm is by the side or if the ROI is away from the isocentre. Chemical/spectral presaturation is effective with the swimmer's positioning. The FSE sequence is optimal as it provides better resolution than STIR.

Image optimization

Technical issues

The inherent contrast is relatively good in this area due to the apposition of muscle and fat. Medium slice thickness and resolution, combined with sensitive coils, permit a fast examination so that high resolution axial images may be acquired for lesions close to the neurovascular bundle and when cortical bone-breach is not obvious. The FOV is usually extended on the coronals and sagittals so that the entire length of the forearm is visualized. This is especially important in the diagnosis of bony tumours to ensure that any additional skip lesions are identified. The associated

13

scan time reductions of FSE enable the implementation of medium to fine matrices, without unduly lengthening the scan time. In the coronal and sagittal planes, a rectangular/asymmetric FOV is useful with the long axis of the rectangle running along the length of the forearm. When using FSE with T2 weighting, the muscles return a lower signal than in SE and fat returns a higher signal. Chemical/spectral presaturation techniques are, therefore, usually necessary to distinguish fat from pathology. Spectral fat suppression is difficult to achieve over a large FOV in the periphery of the homogeneous field, so STIR is typically used in coronal and sagittal images. Axial images near isocentre in the longitudinal direction can usually support chemical fat suppression.

Artefact problems

Patient movement is sometimes troublesome in the swimmer's position as the patient is more likely to be uncomfortable. Careful immobilization, or laying the patient supine instead, is beneficial. Pulsation from the radial vessels is reduced using spatial presaturation pulses placed S and I to the FOV. GMN can also be used but, as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences.

Patient considerations

Patients must be carefully positioned if the swimmer's position is used, and immobilized with foam pads for comfort. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be useful for visualizing some soft tissue abnormalities but it is not routinely used.

13

Wrist and hand

Basic anatomy (Figure 13.23)
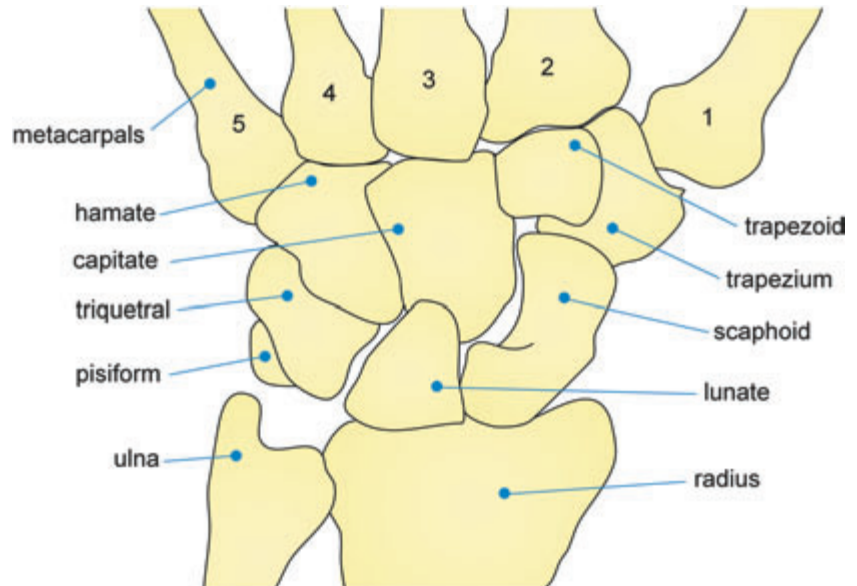
Figure 13.23 Bony structures of the wrist.

Common indications

- Assessment of wrist pain of unknown origin (tears of the triangular cartilage, osteonecrosis of the lunate (Kienböch's disease), occult ganglia).
- Assessment of avascular necrosis (AVN) of the scaphoid following trauma.
- Diagnosis of carpal tunnel syndrome.
- Possibly valuable in early evaluation of rheumatoid arthritis.
- Assessment of the scapholunate and scaphotriquetral ligaments when wrist instability is suspected.

Equipment

- Dedicated wrist coil (volume/Helmholtz/phased or multi-coil array)/ small surface coil(s) linked by a phase harness. Very small, specially designed, local coils can be used to examine finger joints.
- Immobilization pads and straps.
- Ear plugs.

13

Patient positioning

The patient is usually scanned lying supine with the arm by the side with the elbow and wrist facing up to avoid pronation of the forearm. The wrist and hand are placed in a splint to prevent movement, and to aid secure coil placement. Move the patient as far as possible across the table and support the entire arm on pads to bring the wrist as close as possible to isocentre. Fit patients may be able to tolerate the swimmer's position with the palm either facing up or down with the arm bent at the elbow. If a small circular coil is used, the patient can be positioned prone or supine with the arm above the head and elbow bent so that the forearm runs across the table. The coil is fixed in the sagittal plane at vertical isocentre. If two coils are used the wrist is placed through them to take advantage of both of the sensitive areas of the coils. As this requires active coil decoupling check your system's operation manuals if in doubt. If the wrist is at isocentre in all three axes, the longitudinal and horizontal alignment lights are centred to the wrist. If the arm is at the side it may be necessary to measure the horizontal offset with a plastic ruler.

Suggested protocol

Multiplanar/Sagittal SE/FSE/incoherent (spoiled) GRE T1/coherent GRE T2* (Figure 13.24)

Acts as a localizer if three-plane localization is unavailable but, if the patient has been positioned correctly, may act as a diagnostic sequence. Using the body coil, medium slices/gap are prescribed on either side of the longitudinal light in the swimmer's position or on either side of the offset with the arm at the side. The area from the inferior border of the carpal bones to the distal portion of the forearm is included in the image.

L 15 mm to R 15 mm
(swimmer's position)

Axial localizer: This may be prescribed from the multiplanar localizers or the sagittal localizer. Use a surface coil to determine slice orientation for coronal imaging more accurately (Figure 13.25).

Coronal SE/FSE T1 (Figure 13.26)

Thin slices/gap or interleaved are prescribed through the joint or ROI parallel to the proximal row of the carpus as seen from the axial localizers (the distal radioulnar joint is frequently not aligned with the carpus). Displace slices inferiorly for the carpal tunnel. The area from the inferior border of the carpal bones to the distal portion of the forearm is included in the image.

13

Figure 13.24 Sagittal GRE T2* weighted localizer of the wrist showing slice prescription boundaries and orientation for coronal imaging.
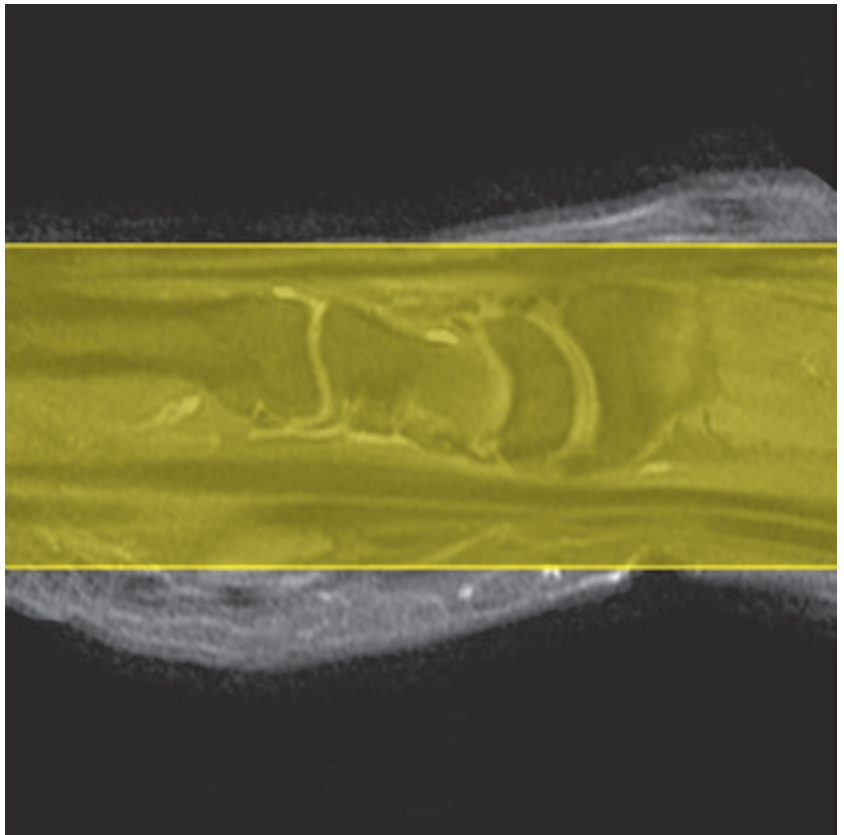
Figure 13.25 Axial GRE T2* weighted localizer of the wrist showing slice prescription boundaries and orientation for coronal imaging.
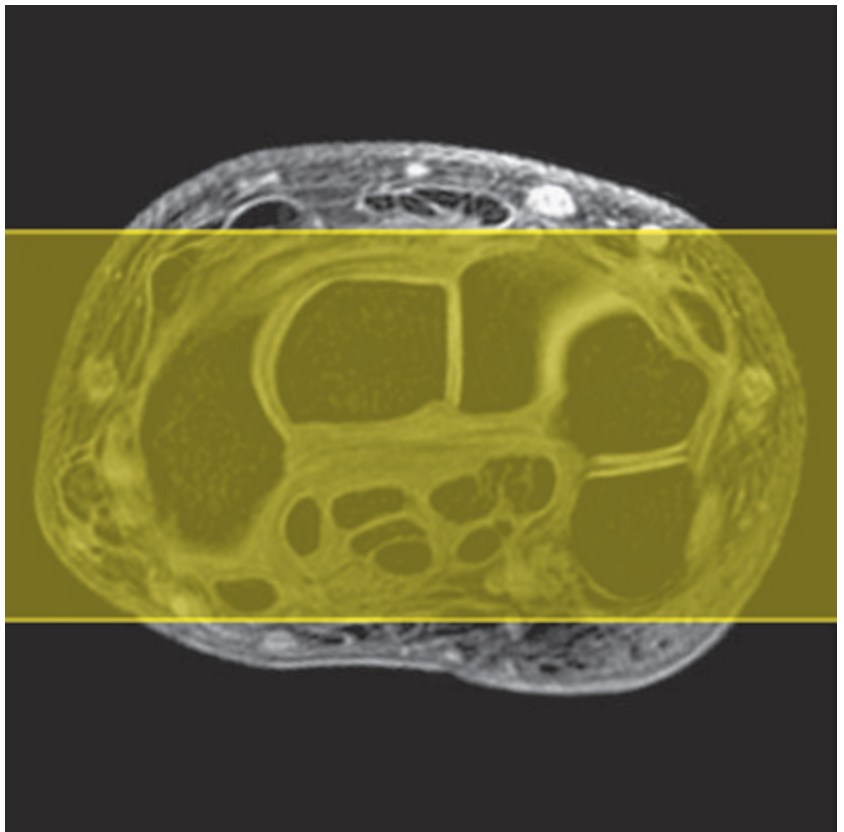
Figure 13.26 Coronal FSE T1 weighted image of the wrist showing normal appearances.

Coronal SE/FSE T2 or coherent GRE T2* +/− chemical/spectral presaturation (Figures 13.27 and 13.28)

Slice prescription as for Coronal T1.

These sequences are useful for investigating the triangular fibrocartilage, fractures or AVN. STIR is not commonly used due to poor SNR and, therefore, good resolution is difficult to obtain.

Axial FSE T2 (Figure 13.29)

Thin slices/gap are prescribed through the ROI orientated parallel to the proximal row of carpal bones as seen on the coronal images (Figure 13.30).

Axial FSE T1 (Figure 13.31)

Slice prescription as for Axial T2.

This sequence is useful for carpal tunnel syndrome and ulnar nerve lesions.

13

Figure 13.27 Coronal coherent GRE T2*.

Figure 13.28 Coronal FSE T2 weighted image of the wrist with chemical/spectral presaturation.

13
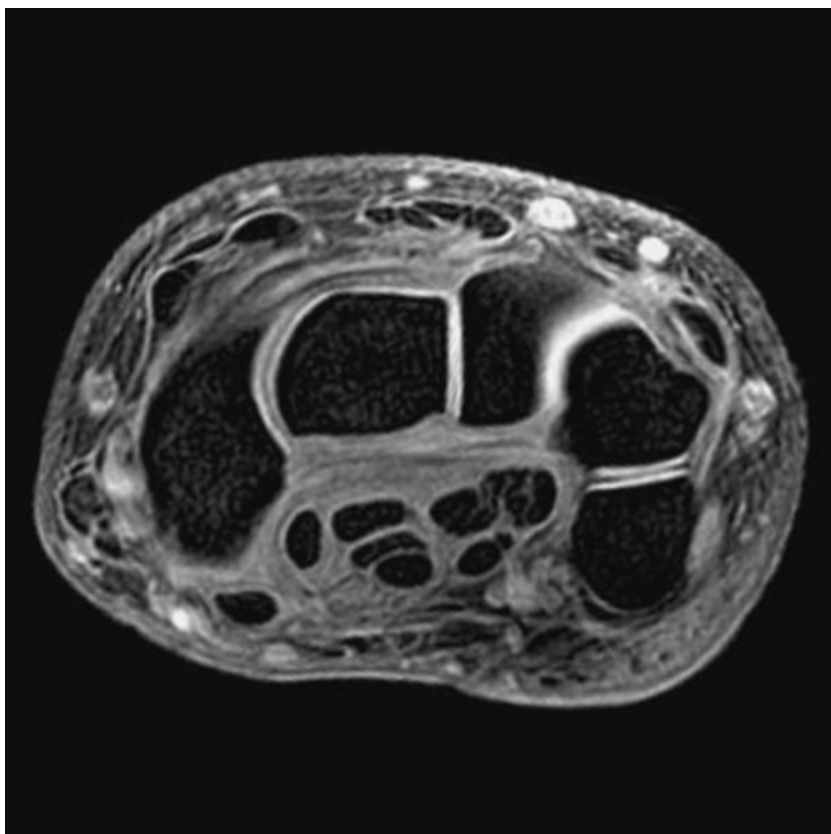
Figure 13.29 Axial FSE T2 weighted image through the carpel tunnel.

13
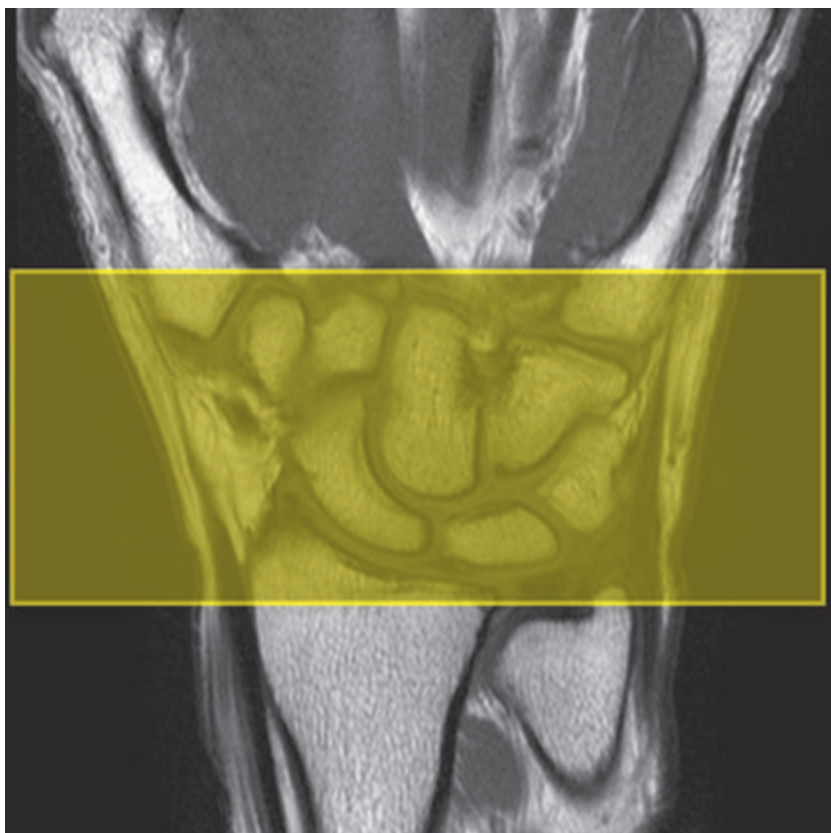
Figure 13.30 Coronal FSE T1 weighted image showing slice prescription boundaries and orientation for axial imaging of the wrist.
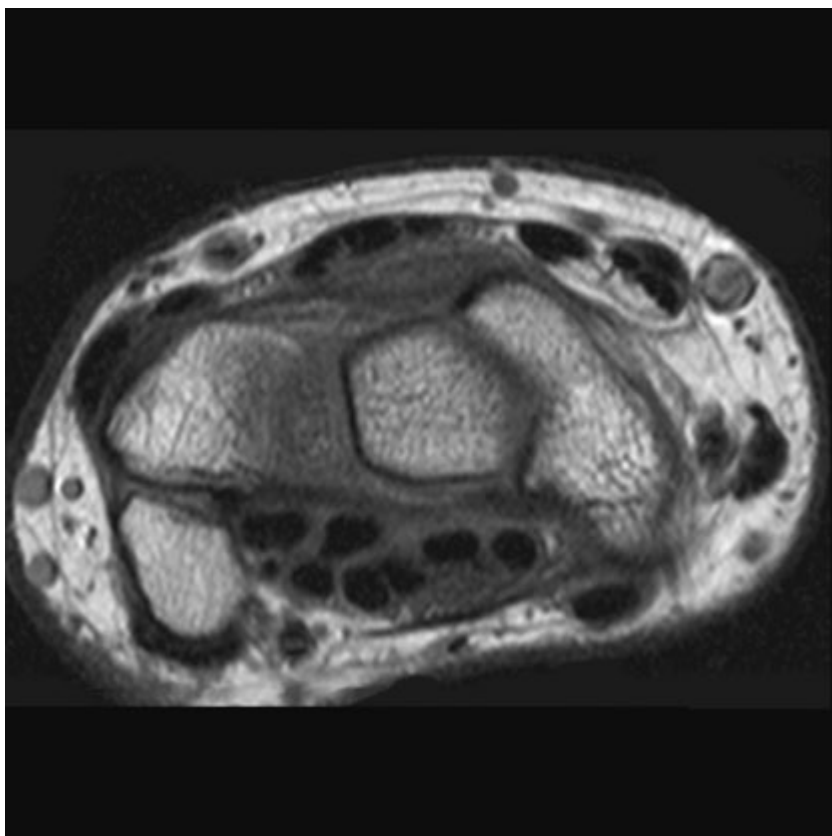
Figure 13.31 Axial FSE T1 weighted image of the wrist clearly demonstrating the carpal tunnel.

Additional sequences

Axial PD + chemical/spectral presaturation (Figure 13.32)

Slice prescription as for Axial T2.

This sequence is useful for visualization of articular cartilage and carpal tunnel.

Sagittal SE/FSE T1

Thin slices/gap are prescribed orientated perpendicular to the coronal plane. This sequence is useful for localizing dorsal ganglia (Figure 13.33).

3D incoherent (spoiled) GRE T1 or coherent GRE T2* (Figure 13.34)

Used to investigate fluid or solid pathologies with thin slices but at the expense of resolution. Hybrid sequences showing anatomy and fluid are also popular. Thin slices and a small number of slice locations are prescribed through the joint allowing for slice wrap.

13
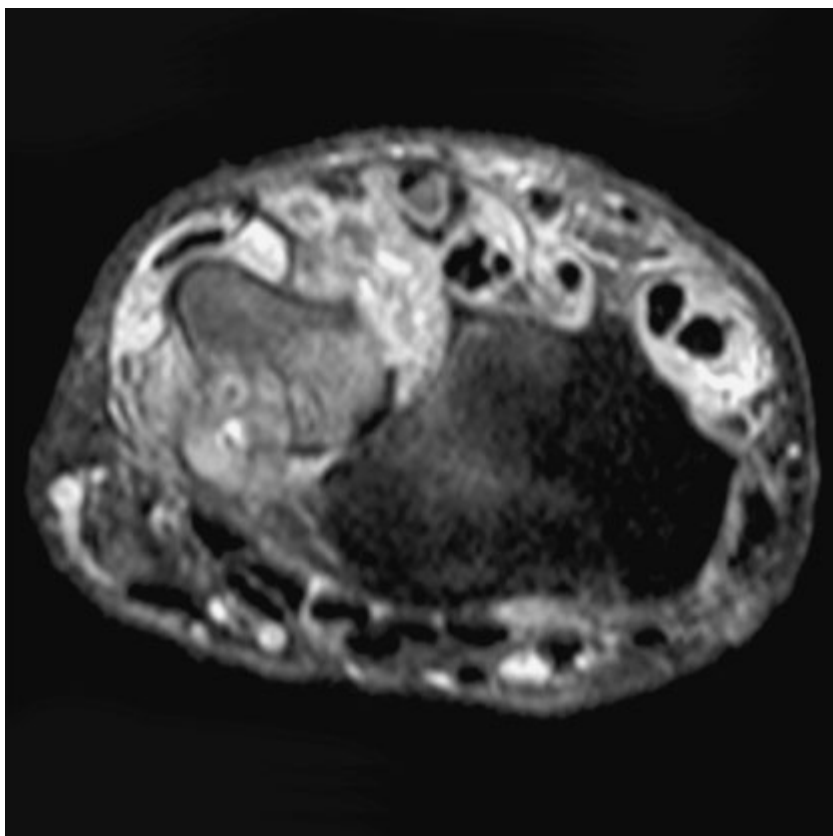
Figure 13.32 Axial FSE PD with chemical/spectral presaturation.

Figure 13.33 Coronal FSE T1 weighted image showing slice prescription boundaries and orientation for sagittal imaging of the wrist.

Figure 13.34   Coronal slice from a 3D T1 weighted data set.

Image optimization

Technical issues

The quality of the coil is very important in the wrist. The inherent SNR and CNR are relatively low as most of the structures are bony, and there is little fat. The use of a dedicated wrist coil ensures a high and uniform signal return, so that the high resolution required in the wrist is easily obtained. Multiple NEX/NSA may also be necessary to improve the SNR. Very small, specially designed, surface coils may be used to examine the fingers individually. However, this type of examination is not very common at present.

High spatial resolution is essential to display the fine anatomy of the wrist adequately and therefore fine matrices and thin slices and interleaving are required. FSE is commonly utilized although longer ETLs and echo spacing may induce significant blurring, or compromise the diagnosis of tendon pathology in T1 weighted images (see *Pulse sequences* in Part 1).

13

Artefact problems

There is little artefact in this area as the vessel pulsations are not particularly strong but spatial presaturation pulses placed S and I to the FOV reduce phase ghosting. GMN is not usually required to decrease flow artefact in the wrist but it effectively increases the contrast of the synovial fluid in T2 and T2* weighted images. Patient movement may be troublesome in the swimmer's position, especially if the scan times are lengthy. It is, therefore, necessary to ensure that the patient is carefully immobilized and comfortable. Instruct the patient not to move their fingers during the sequences. Motion induced by discomfort is often a problem no matter what positioning is used. Fat suppression is difficult in the periphery of the homogenous region of the magnet. Shimming improves chemical fat suppression and the quality of longer TE GRE sequences. All metal should be removed from the patient's clothing and body to preserve a good shim. RF blankets or shields can be used to screen signal from the patient's body, obviating the need for oversampling in many cases. Alternatively, spatial presaturation pulses can be used to null signal from the body.

Patient considerations

Inform the patient of the possibly lengthy scan times and the importance of keeping still. Ensure that the patient is comfortable and well immobilized.

Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely used in the wrist; however MR arthrography is sometimes useful in increasing the certainty of seeing perforations of the ligaments and triangular fibrocartilage.

13

14

Lower limb

14

Table 14.1   Summary of parameters. The figures given are general and should be adjusted according to the system used (Table 2.1)

Spin echo (SE)			**Coherent GRE**		
short TE	min to 30 ms		long TE	15 ms +	
long TE	70 ms +		short TR	≤ 50 ms	
short TR	300−600 ms		flip angle	20°−40°	
long TR	2000 ms +				
Fast spin echo (FSE)			**Incoherent GRE**		
short TE	min−20 ms		short TE	min−5 ms	
long TE	90 ms +		short TR	≤ 50 ms	
short TR	400−600 ms		flip angle	20°−40°	
long TR	4000 ms +				
short ETL	2−6				
long ETL	16 +				
Inversion recovery (IR) T1			**Balanced GRE**		
short TE	min−20 ms		TE	minimum	
long TR	3000 ms +		TR	minimum	
medium TI	200−600 ms		flip angle	≥ 40°	
short ETL	2−6		**SSFP**		
STIR			TE	minimum	
long TE	60 ms +		TR	40−50 ms	
long TR	3000 ms +		flip angle	20°−40°	
short TI	100−175 ms				
long ETL	12−20				
FLAIR					
long TE	60 ms +				
long TR	3000 ms +				
long TI	1700−2200 ms				
long ETL	12−20				

Slice thickness			**Slice numbers**			
2D	thin	2−4 mm	Volumes	small	≤ 32	
	medium	5−6 mm		medium	64	
	thick	8 mm		large	≥ 128	
3D	thin	≤ 1 mm	**Matrix (frequency × phase)**			
	thick	≥ 3 mm	coarse	256 × 128 or 256 × 192		
			medium	256 × 256 or 512 × 256		
			fine	512 × 512		
			very fine	≥ 512 × 512		

FOV			**PC-MRA**		
small	≤ 18 cm		2D and 3D	TE	minimum
medium	18−30 cm			TR	25−33 ms
large	≥ 30 cm			flip angle	30°
			VENC venous	20−40 cm/s	
			VENC arterial	60 cm/s	
NEX/NSA			**TOF-MRA**		
short	≤ 1		2D	TE	minimum
medium	2−3			TR	28−45 ms
multiple	≥ 4			flip angle	40°−60°
			3D	TE	minimum
				TR	25−50 ms
				flip angle	20°−30°

14

Hips

Basic anatomy (Figure 14.1)

anterior superior
iliac spine

iliofemoral ligament

greater trochanter

pubofemoral ligament

obturator foramer

pubic ramus

lesser trochanter
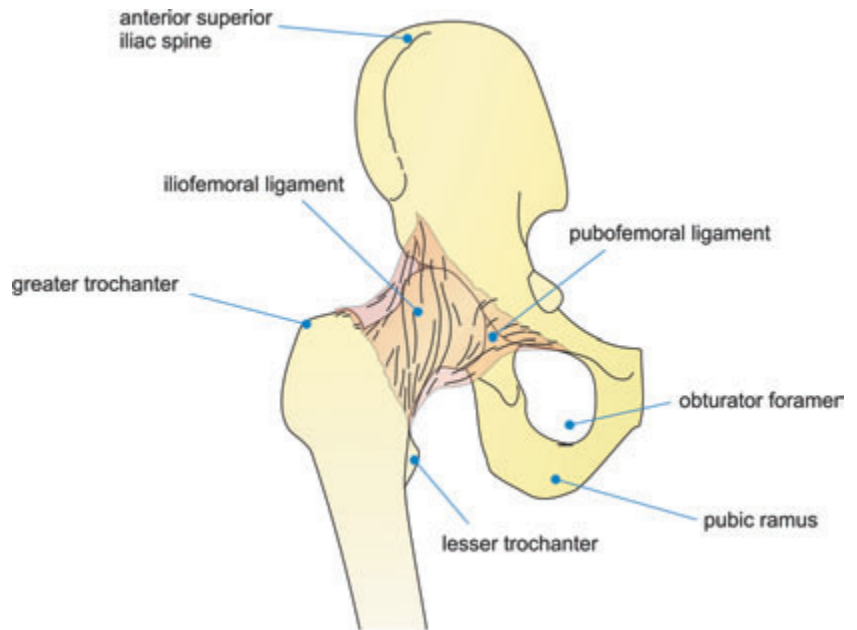
Figure 14.1   Anterior view of the right hip demonstrating bony components and ligaments.

Common indications

- Evaluation of unexplained unilateral or bilateral hip pain.
- Suspected occult fracture.
- Muscle tears.
- Labral tears, chondral damage or other joint soft tissue pathology.

Note: Bilateral and unilateral examinations of the hips are described in this section. The causes of generalized hip pain include AVN, metastatic deposits and occult fractures, which may affect both hips. Specific unilateral joint pathologies such as suspected labral tears or chondral damage require high-resolution imaging of the hip in question. However, due to the prevalence of AVN in patients presenting with hip pain, it is advisable to include a bilateral sequence in unilateral hip protocols.

Equipment

14

Bilateral hip imaging

- Body phased array/multi-coil array/general-purpose flexible coil/ body coil.

- Immobilization pads and straps.
- 20° wedge sponges.
- Ear plugs.

Single hip imaging

- Small/large flexible coil/multi-coil array/pelvis phased array/small Helmholtz pair.
- Immobilization pads and straps.
- 20° wedge sponges.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with their legs straight and both feet parallel to each other. This ensures that the angle of both femoral necks is the same, although they do not necessarily have to be internally rotated as in radiography of the hips. The legs are immobilized with the use of pads and straps wrapped around both feet. This enables the patient to maintain the position in a relaxed fashion.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the femoral heads. They are localized by palpating the femoral pulse, which is typically found 3 cm inferiorly and laterally to the midpoint of the line joining the anterior superior iliac spine (ASIS) and the pubic symphysis. If only one hip is imaged the FOV will be offset from isocentre and image quality may be affected.

Suggested protocol – bilateral examination

Axial SE/FSE/incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gap are prescribed on either side of the horizontal alignment light. Both hips are included to show the location and alignment of the hips.

Axial I 25 mm to S 25 mm

Coronal FSE T2 +/– chemical/spectral presaturation/STIR

Thin slices/gap are prescribed from the posterior to the anterior margins of the musculature of the hip (from the iliacus to the anterior portion of gluteus maximus). Slices may be angled to compensate for positional rotation of the pelvis. The images should display the lateral edges of the muscles surrounding the hips (gluteus medius), and extend from the junction of the ilium and the superior acetabulum to below the lesser trochanter.

14

Figure 14.2 Coronal FSE T1 image of both hips and femora.

Coronal SE/FSE T1 (Figure 14.2)

Slice prescription as for Coronal T2.

Axial SE/FSE T1

Thin slices/gap are prescribed from above the articular portion of the acetabulum to the superior edge of the lesser trochanter, and aligned with the superior surface of both femoral heads to correct for positional errors (Figure 14.3).

Sagittal FSE T2/coherent GRE T2* +/− chemical/spectral presaturation

Thin slices/gap are prescribed from the lateral aspect of the greater trochanter through the articular portions of the acetabulum (Figure 14.4). These images particularly demonstrate flattening of the femoral head associated with AVN. Generally, FSE is the sequence of choice but GRE sequences provide excellent visualization of cartilage.

14
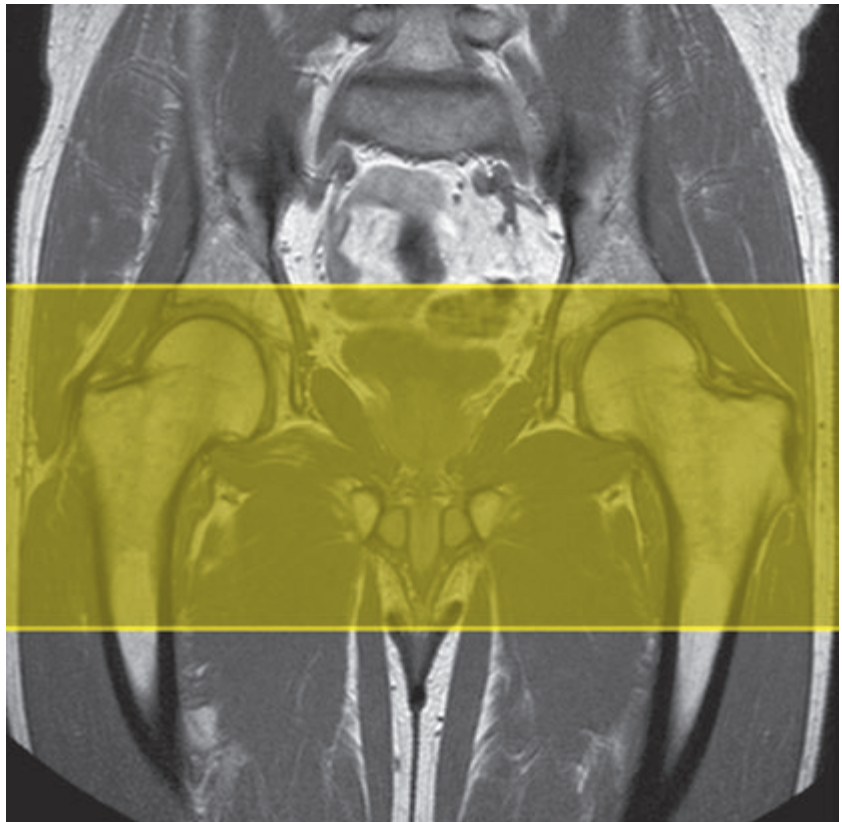
Figure 14.3 Coronal FSE T1 weighted image showing slice prescription boundaries and orientation for axial imaging of the hips.
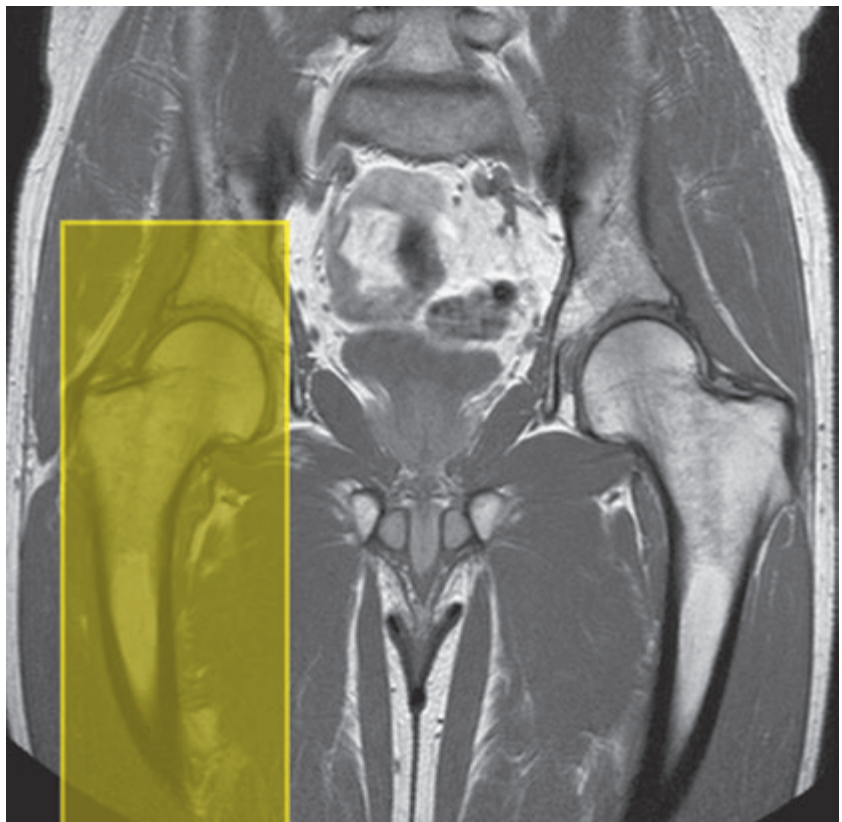
Figure 14.4 Coronal FSE T1 weighted image showing slice prescription boundaries and orientation for sagittal imaging of the hips.

Suggested protocol – unilateral examination

This examination usually demands higher resolution than bilateral exams. Image planes should be placed relative to the anatomy of the joint rather than orthogonal to the body. Extra shimming may be required to optimize chemical/spectral presaturation performance and GRE image quality in an offset FOV.

Axial SE/FSE/incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. As for bilateral examination. Use the body coil and include both hips.

Coronal SE/FSE T1

Thin slices/gap are prescribed from the posterior to the anterior margins of the femoral head and aligned parallel to the femoral neck. The area from the proximal margin of the femoral shaft (below the lesser trochanter) to the greater sciatic notch is included in the image.

Coronal coherent GRE T2*/FSE T2 +/– chemical/spectral presaturation

Slice prescription as for the Coronal T1.

T2* images are particularly good for identifying the labrum and loose bodies in the joint. A FSE T2 may be preferred to provide higher resolution.

Axial FSE T2 +/– chemical/spectral presaturation

Thin slices/gap are prescribed from a coronal image to include the articular components of the hip joint. Angle the slices so that they are parallel to the femoral neck.

Axial SE/FSE/incoherent (spoiled) GRE T1

Slice prescription as for Axial T2.

Additional sequences

Coronal FSE T2 +/– chemical/spectral presaturation (both hips)

This may be used as an additional sequence to the unilateral examination, especially to rule out AVN of the asymptomatic hip. Use the body coil to avoid repositioning of the patient. Medium slice/gap is adequate as the contrast sensitivity of the sequence should identify pathology. Position slices to include the bony components of the hip joint and some surrounding musculature.

14

Figure 14.5   Coronal arthrogram.

SE/FSE/incoherent (spoiled) GRE T1 + contrast (Figures 14.5 and 14.6)

This sequence may be used after intra-articular injection of contrast to visualize labral tears and chondral defects. A very dilute solution of gadolinium contrast agent in saline (1 : 100) is introduced into the joint capsule and the single joint is imaged at high resolution with chemical/spectral presaturation. T1 weighted images in three planes are acquired aligned to the femoral neck and acetabular rim.

Image optimization

Technical issues

Spatial resolution is a critical parameter in joint imaging and depends on the clinical indications. For example, when examining small labral tears, resolution is paramount and utilization of thin slices/gap and a fine matrix is necessary. However, when the lesion is large and CNR is high, resolution can be sacrificed to achieve better SNR or shorter scan times. Volume

14
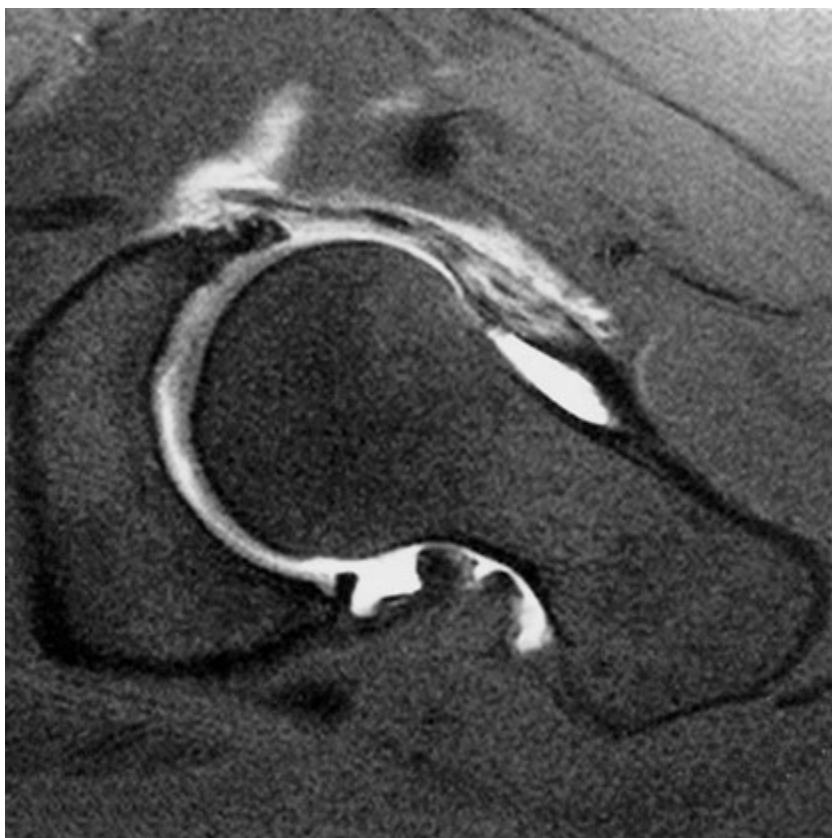
Figure 14.6 Axial arthrogram.

acquisitions are sometimes valuable as very thin slices with no gap are used, and joint structures may be visualized in any plane. As volume acquisitions are usually performed in order to demonstrate anatomy, an incoherent (spoiled) GRE sequence that produces predominantly T1 weighting is required.

Bilateral and unilateral examinations have been described in this section. Bilateral imaging with a large phased array coil has a number of advantages. It can provide acceptable resolution for visualizing joint structures when used with a combination of a small FOV and oversampling, but it can also be utilized with a large FOV to provide medium-resolution images of a large area of anatomy. For unilateral examinations the requirement for fine spatial resolution is paramount. The hip joint structures are comparable in size to the shoulder, demanding spatial resolution of less than 0.5 mm. Unfortunately, the relatively bulky musculature and the external morphology of the hip demands physically larger coils. As a result it may be necessary to use higher NEX/NSA and longer scan times to achieve acceptable SNR.

Flexible selection of a rectangular/asymmetric FOV has greatly helped to tailor hip sequences in the axial and sagittal planes. In addition, flexible

14

application of oversampling allows a small FOV to be used in the coronal and axial planes in conjunction with larger coils, as well as providing finer incremental changes in SNR.

Several sequences are employed in hip examinations. SE sequences usually provide better contrast and resolution in T1 weighted images than FSE. However, the development of high-performance gradients, which permit short ETLs and echo spacing improve resolution. Chemical/spectral presaturation is an important imaging option in the musculoskeletal system, as the suppression of normal fatty marrow often enhances the visualization of bony pathology. Chemical/spectral presaturation techniques are usually preferred, but STIR sequences provide very uniform fat suppression, particularly on older systems and in large FOVs. In addition, there is a developing trend to use moderate to short TEs for fat suppressed T2 weighted FSE sequences (30–50 ms), which yield high SNR and CNR. The efficacy of this approach has not yet been established. Additional shimming may be required before chemical/spectral presaturation sequences.

While reduced bandwidth sequences offer SNR increases without serious time penalties, the bandwidth should be chosen to limit the chemical shift to one or two pixels for most hip examinations and particularly when producing high-resolution images.

Artefact problems

The main source of artefact is from flow within the femoral and iliac vessels. Spatial presaturation pulses placed S and I to the FOV reduce this to a large degree. When imaging a single hip for labral tears, bowel motion may be troublesome. Placing a spatial presaturation pulse medial to the hip effectively reduces this. GMN further minimizes flow artefact but, as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. However, GMN can effectively increase contrast in synovial fluid in T2 and T2* weighted images.

Hip prosthesis or pins produce significant magnetic susceptibility artefact. This can sometimes, but not always, ruin an image. Do not use a GRE sequence as gradients do not compensate for magnetic field inhomogeneities, thereby increasing magnetic susceptibility artefact. To minimize the artefact, select SE or FSE sequences in conjunction with a broad receive bandwidth. The artefact can sometimes be shifted away from the ROI by swapping the phase and frequency encoding directions but this, in turn, may lead to aliasing. However, aliasing can be avoided by oversampling and careful location of the hands away from the side of the body and on to the chest.

14

Patient considerations

Patients with a hip prosthesis may experience warmth during the examination. Warn them that this may occur and provide them with an emergency bell in case any discomfort is noticed. Due to excessively loud gradient

noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

IV contrast is virtually never indicated in hip joint imaging unless as an indirect MR arthrography technique (see *Shoulder* in *Upper Limb*). Direct MR arthrography of the hip is an important technique in the diagnosis of some hip disorders, especially labral tears.

14

Femur

Basic anatomy (Figure 14.7)
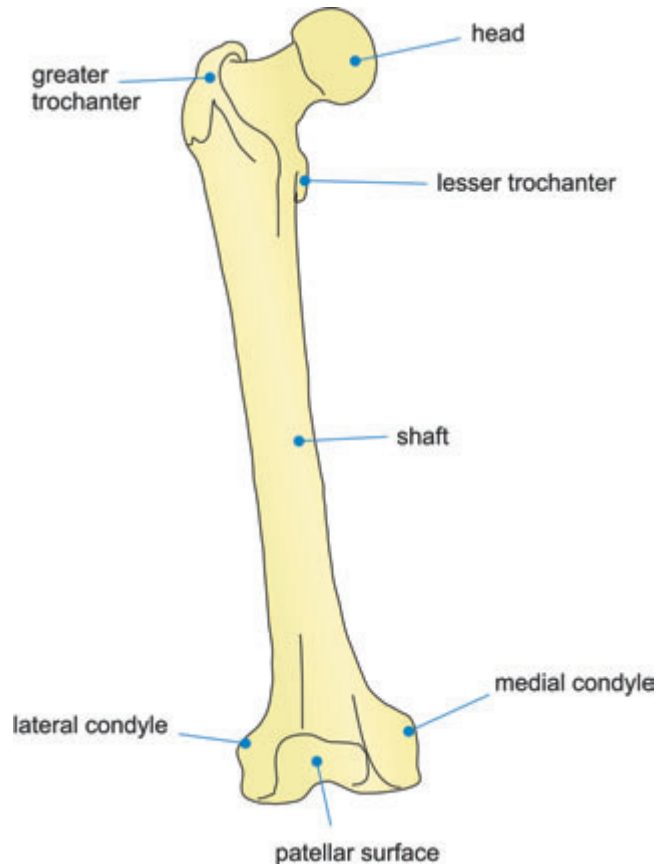
Figure 14.7 Anterior view of the right femur.

Common indications

- Assessment of suspected or known pathology of soft tissues and bone (tumours, infection, muscle tears).

A bilateral examination is recommended for all new cases, but single-sided imaging can be used for follow-up examinations, particularly if an array coil is unavailable.

Equipment

- Body array coil for imaging both, or one femur (offset the anterior and posterior portions slightly to cover the entire femur)/body coil

for both femora/long surface coil placed under the femur if only one leg is under examination and the ROI is localized posteriorly in the thigh.

- Immobilization pads and straps.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with their legs straight and their feet in a comfortable position. The feet are immobilized in this position using pads and straps. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the knee and the hip (or over the ROI if this is known). If only one side is to be imaged the patient should be moved until the femur is as close as possible to the midline of the bore. Use the plastic ruler to measure from the horizontal alignment light to each joint to ensure the full femur fits within the long axis of the FOV. If not, include either the knee or hip depending on the location of the lesion(s). When a lesion is palpable place an oil- or water-filled marker over it for easy localization. For large lumps or scars place a marker at each end.

Suggested protocol

Axial/Coronal/Multiplanar SE/FSE T1/T2 or incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Axial localizers are useful to locate lesions in the SI axis but do not indicate if the full length of the femur will be included in the other planes. Coronal localizers locate lesions situated in the RL axis. Medium slices/gap are prescribed from skin surface to skin surface. In the coronal plane the entire length of the femur should be included in the image.

Axial localizer: I 100 mm to S 100 mm
Coronal localizer: P 50 mm to A 40 mm

Sagittal STIR

Medium slices/gap are prescribed to include the entire thigh and aligned parallel to the long axis of the femur. If bilateral lesions are suspected repeat this sequence on the other leg.

Coronal SE/FSE T1

Medium slices/gap are prescribed to include the entire thigh from the anterior to the posterior skin surfaces and aligned parallel to the long axis

14

of the femur. This sequence enables visualization of both femora for comparison and identification of lesions in the marrow space.

Axial SE/FSE T1

Medium slices/gap are prescribed to extend from well below to well above lesions seen on the coronal or sagittal images. Axial images are useful for localizing lesions within significant anatomical compartments. Breach of the marrow space, extension within or through muscle compartments, and association with the neurovascular bundle are all significant characteristics.

Axial SE/FSE T2 +/– chemical/spectral presaturation

Slice prescription as for the Axial T1.

Image optimization

Technical issues

The inherent contrast is relatively good in this area due to the apposition of muscle and fat. This, combined with sensitive coils and the use of medium-resolution imaging, permits relatively fast examinations in the sagittal and coronal planes. As a result more time can be spent acquiring higher-resolution axial images when necessary. Lesions close to the neurovascular bundle or subtle cortical bone breaches are examples of when this strategy might be utilized.

A surface coil increases the signal substantially as compared with the body coil, but signal fall-off in the anterior part of the thigh often prohibits its use. The body array coil must be positioned to provide coverage of the entire thigh. Total coverage of both femora is necessary in the evaluation of bony tumours to ensure that additional skip lesions are detected. Good spatial resolution is usually achievable especially if FSE is used, as fine matrices can be selected without unduly lengthening the scan time.

A rectangular/asymmetric FOV can be implemented in the sagittal and axial planes with the long axis of the rectangle either R to L or S to I, respectively. Chemical/spectral presaturation techniques are commonly utilized, especially in FSE T2 weighted images, where the signal from fat remains bright and may return a similar signal to pathology. Additional shimming may be required before chemical/spectral presaturation sequences. In T2 FSE, the signal returned from muscle is usually lower than in SE, thereby increasing conspicuity of some lesions. To enable accurate characterization of a new lesion, MRI must be performed before tissue biopsy or partial excision.

Artefact problems

Chemical shift artefact must be kept within one pixel, particularly in axial images, to delineate the interface of marrow and cortical bone and the

14

edges of muscle compartments clearly. Flow artefact from the femoral vessels is the main source of phase ghosting in this area. Spatial presaturation pulses placed S and I to the FOV reduce this effectively. GMN minimizes the artefact but, as it increases the minimum TE, it is not usually beneficial in T1 weighted sequences.

Patient considerations

Patients with a hip prosthesis may experience warmth during an examination of the femur especially if there is a long femoral component. Warn them that this may occur and provide them with an emergency bell in case any discomfort is noticed. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely used in the femur. It may, however, be useful for tissue characterization of certain tumours.

14

Knee

Basic anatomy (Figures 14.8 and 14.9)
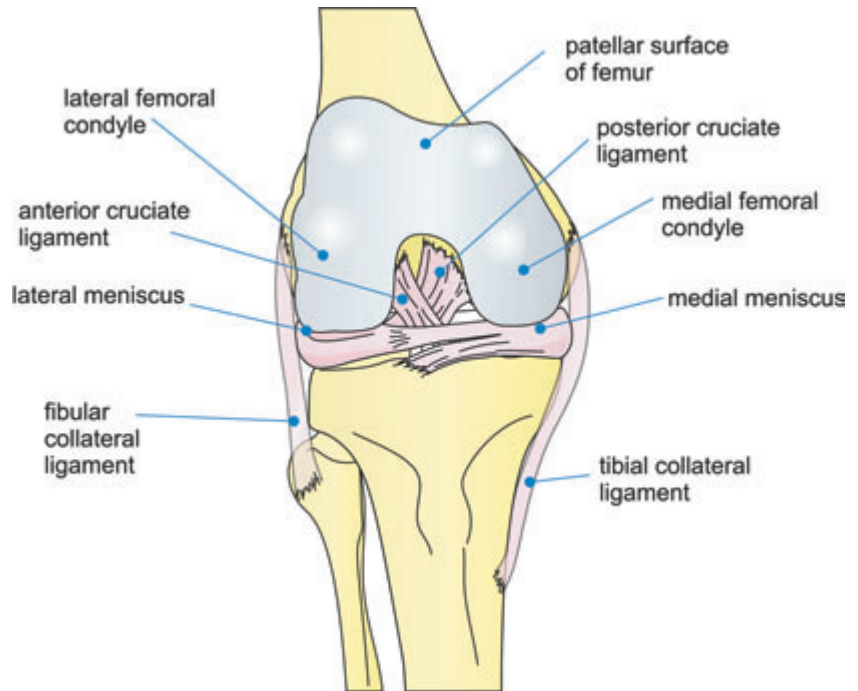
Figure 14.8 Anterior view of the right knee showing internal joint structures and ligaments.

Labels: patellar surface of femur, lateral femoral condyle, posterior cruciate ligament, anterior cruciate ligament, medial femoral condyle, lateral meniscus, medial meniscus, fibular collateral ligament, tibial collateral ligament

14
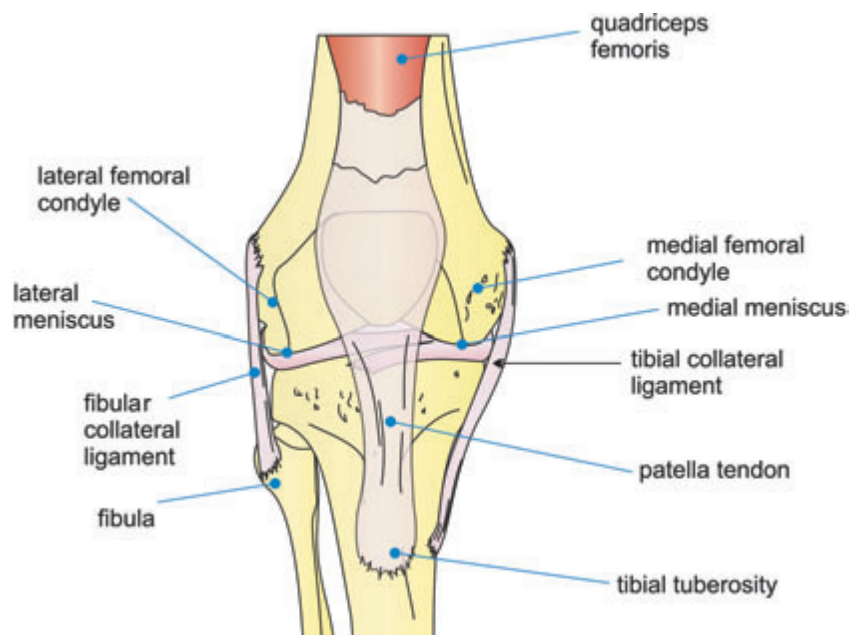
Figure 14.9 Anterior view of the right knee external structures and ligaments.

Labels: quadriceps femoris, lateral femoral condyle, medial femoral condyle, lateral meniscus, medial meniscus, fibular collateral ligament, tibial collateral ligament, patella tendon, fibula, tibial tuberosity

Common indications

- Internal derangement of the joint (meniscal tears, cruciate ligament tears, post-repair cruciate ligament tears, bursae).
- Chondromalacia patella and patella tracking.
- Bone tumours and bony damage within the knee joint.
- Almost all other knee disorders can also be visualized.

Equipment

- Knee phased array coil/extremity knee coil/pair of small circular coils combined as a phased/multi-coil array/large flexible coil.
- Immobilization pads.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with their knee in a relaxed, slightly flexed position within the coil. The knee is well immobilized with pads. The coil can be offset so that the other leg rests comfortably at the side. The patient is positioned so that the longitudinal alignment light lies either along the midline of the leg under examination, or displaced from it if the knee has been offset. The horizontal alignment light passes through the centre of the coil. The knee is placed within the coil so that the centre of the coil corresponds to the lower border of the patella.

A clear display of the anterior cruciate ligament is essential in knee examinations for pain, trauma or suspected joint damage. The ligament is best seen in oblique sagittal scans oriented to the appropriate anatomical plane. If your equipment is not capable of oblique imaging, or oblique scan prescription compromises other significant technical choices, the patient's knee should be positioned with a slight (5–10°) external rotation (under-rotation is better than over-rotation). If the scanner can only employ a single-plane oblique, the sagittal scan plane can be prescribed along the internal margin of the lateral femoral condyle from an axial localizer. A more accurate approach is described within the *Suggested protocol* section below.

Suggested protocol

14

Axial/multiplanar coherent gradient echo T2* (Figure 14.10)

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. If the knee is not at isocentre, the FOV is offset so that the knee is in the middle of the image. Medium slices/gap are prescribed on
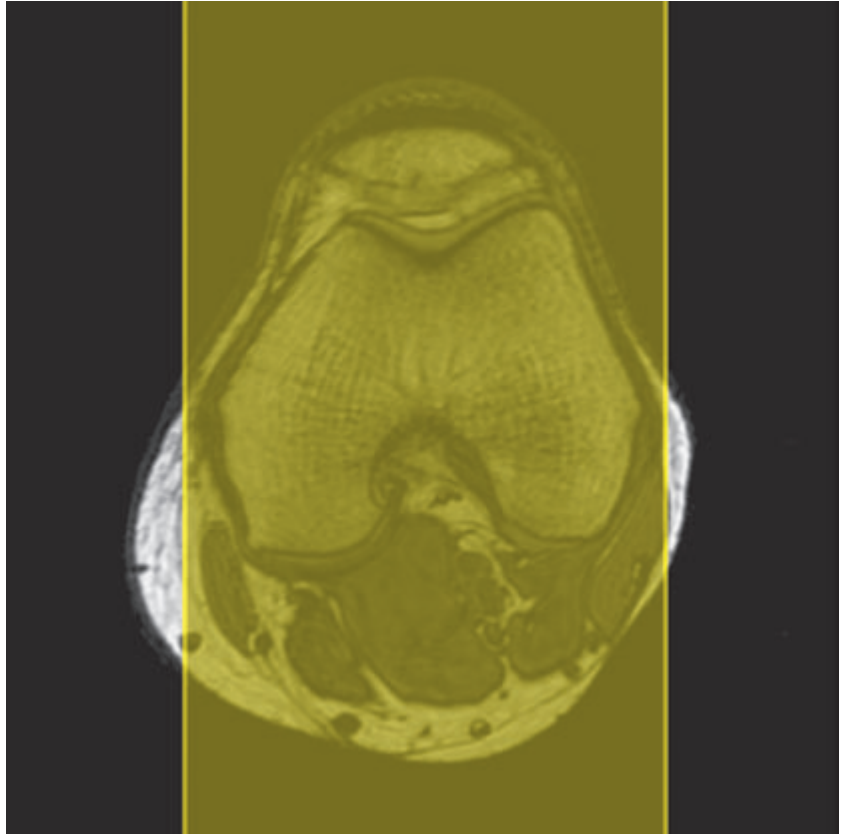
Figure 14.10 Axial T1 weighted localizer of the knee showing slice prescription boundaries and orientation for sagittal imaging.

either side of the horizontal alignment light to locate the knee and ensure correct positioning.

Axial localizer: I 10 mm to S 10 mm

With an axial localizer, a slice in which the patella is clearly demonstrated is chosen to prescribe the following sequences as this ensures that the knee joint is centred to the FOV. If coronal or sagittal localizers are used the knee joint should be in the middle of the image.

Sagittal coherent GRE T2* (Figure 14.12)

Thin slices/gap are prescribed from the lateral to the medial collateral ligament and aligned parallel with the anterior cruciate ligament which runs at an angle (5–10°). The superior edge of the patella to below the tibial tuberosity is included on the image (Figure 14.11).

Coronal FSE PD/T2 +/− chemical/spectral presaturation/STIR (Figures 14.14 and 14.15)

Medium slices/gap are prescribed from the femoral condyles posteriorly to the anterior patella, and orientated parallel to the posterior surfaces of

Figure 14.11 Axial T1 weighted localizer of the knee showing angled slice prescription boundaries and orientation for sagittal imaging of the anterior cruciate ligament.

14
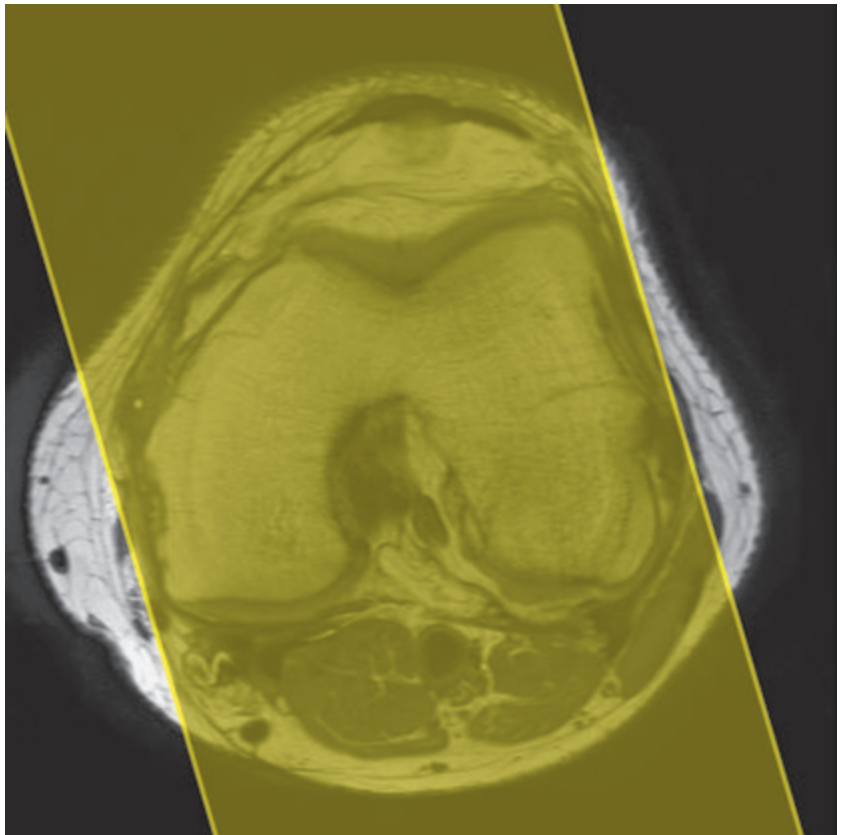
Figure 14.12 Sagittal coherent GRE T2* weighted image of the knee with spectral presaturation.
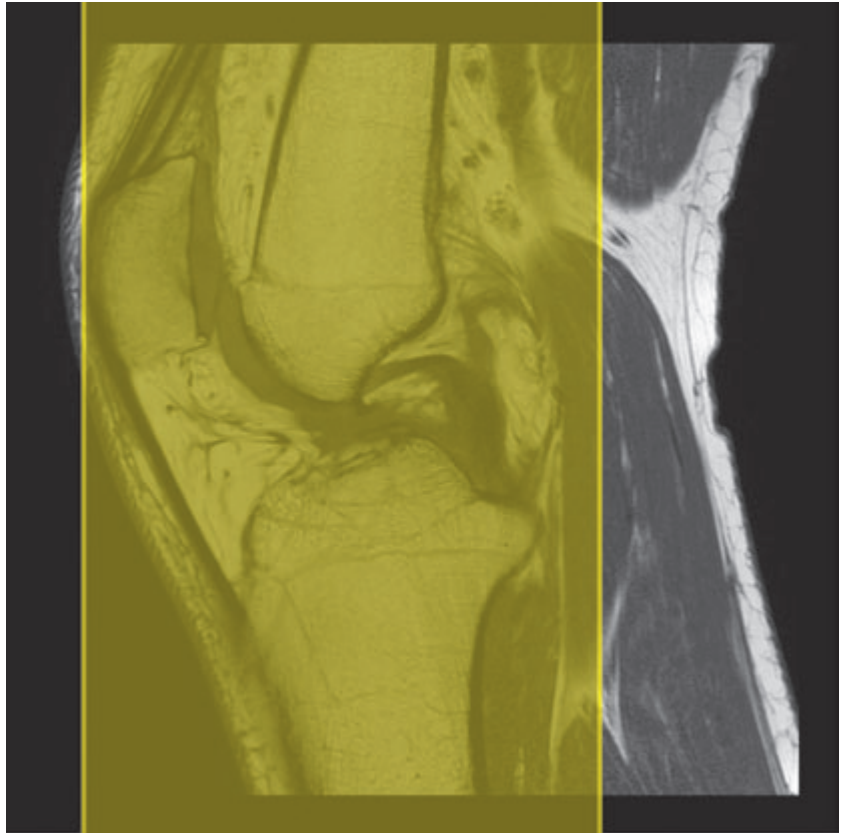
Figure 14.13 Sagittal coherent GRE image showing slice prescription boundaries and orientation for coronal imaging of the knee.

the femoral condyles (Figure 14.13). The superior edge of the patella to the inferior edge of the tibial tuberosity is included in the image.

Coronal SE/incoherent (spoiled) GRE T1 (Figure 14.16)

Slice prescription as for Coronal T2.

This sequence is useful to demonstrate joint anatomy, meniscal tears, musculature, and the collateral ligament complexes. Due to great differences in equipment and sequence performance, FSE should not be used in this application unless the ETL is very short and the accuracy of your sequences in identifying meniscal tears, compared with SE or incoherent (spoiled) GRE, has been tested. The receive bandwidth should be selected to reduce chemical shift to less than two pixels otherwise the femoral or tibial cartilage may be obscured.

Axial FSE PD/T2 +/− chemical/spectral presaturation (Figure 14.17)

Thin slices/gap are prescribed from the superior surface of the patella to the tibial tuberosity. Thin axial slices are essential for patellar tracking

14

Figure 14.14 Coronal FSE PD weighted image of the knee.

Figure 14.15 Coronal STIR image of the knee.

Figure 14.16 Coronal FSE T1 weighted image of the knee.

14

Figure 14.17 Axial FSE PD weighted image of the knee.

problems and to identify chondral damage of the patella and anterior femoral condyles. Images can be repeated with the knee at various degrees of flexion in order to track patella tracking (*see Dynamic imaging* under *Pulse sequences* in Part 1).

Additional sequences

Axial SE/FSE T1

Thin slice, high-resolution imaging is required if patellar tendonitis is suspected.

3D coherent GRE PD/T2* (Figure 14.18)

Thin slices with a medium to large number of slice locations and an isotropic dataset are required to view anatomy in any plane. This is especially useful if evaluation of anatomy and pathology is difficult. Sagittal acquisitions large enough to include the entire knee, from above the patella to below the tibial tuberosity, are necessary.
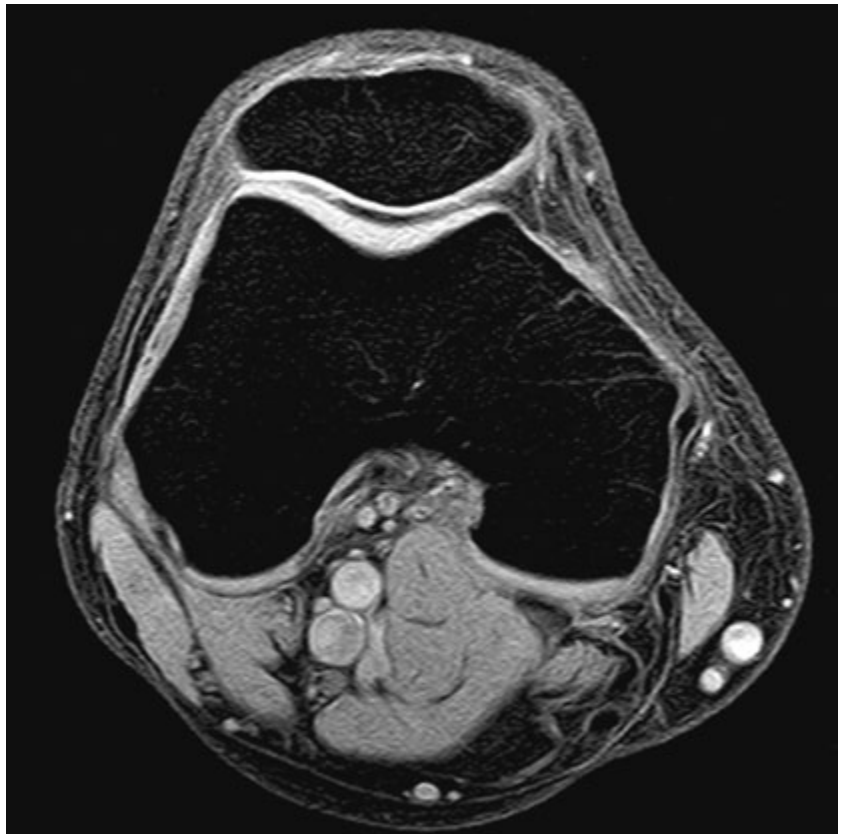
Figure 14.18 Axial slice from a 3D acquisition using spectral presaturation.

14
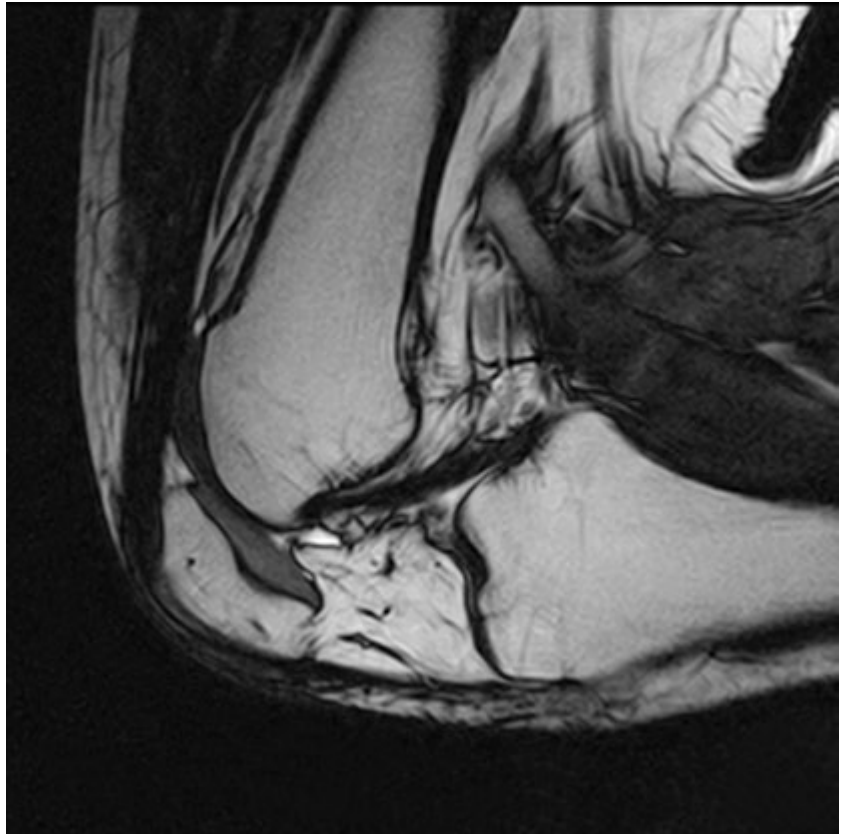
Figure 14.19 Sagittal T1 weighted image of a flexed knee during a dynamic study.

Dynamic imaging (Figure 14.19)

Some open systems, including small bore magnets designed for orthopaedic imaging permit dynamic imaging of joints. In the knee this is particularly useful for visualizing patellar tracking but may also be used to image other structures during movement.

Image optimization

Technical issues

Due to the design of most coils, the SNR in the knee is usually good. These are often transmit and receive coils and therefore ensure optimum and uniform signal coverage. In addition, the muscle, fluid and fat components of the knee give good inherent contrast. Excellent spatial resolution is usually necessary, especially when meniscal tears are suspected. Therefore, thin slices/gap and fine matrices are required. For assessment of the retropatellar region, a surface coil placed directly over the patella

provides very good SNR and permits high-resolution imaging. When utilizing chemical/spectral presaturation techniques a reduced bandwidth increases the SNR considerably and should therefore be employed when possible. Additional shimming may be required before chemical/spectral presaturation sequences.

High-resolution, fat-suppressed images with mild to strong T2 weighting are essential to display occult trabecular fractures, lateral and medial joint effusions and pannus formation. PD fat-suppressed images provide good demonstration of articular cartilage and collateral ligaments, and may adequately visualize meniscal tears (depending on the gradient system's capacity to deliver a short echo spacing). However, coherent GRE T2* sequences are usually necessary to demonstrate meniscal pathology.

A 3D acquisition with an isotropic dataset is useful to provide high-resolution visualization of anatomy in any plane. A PD weighted coherent GRE sequence is most typically employed to demonstrate anatomy and meniscal tears. Dual GRE sequences provide the same weighting but with additional high signal in fluid, which demonstrates joint effusions and provides good contrast with the articular cartilage. These sequences are, therefore, preferred for examining injured joints, despite a significant reduction of meniscal tear conspicuity. An AP phase encoding axis permits the use of a rectangular/asymmetric FOV to reduce scan times.

Artefact problems

The main source of artefact is from popliteal vessel pulsation and patient movement. Presaturation pulses placed S and I to the FOV compensate adequately in most cases; however, phase ghosting can sometimes obscure the joint especially in sagittal imaging. Swapping the phase axis so that it lies S to I removes the artefact from the joint. However, in these circumstances oversampling is necessary to eliminate aliasing from the thigh and the lower leg.

GMN further minimizes flow artefact but, as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. However, GMN effectively increases the contrast of the synovial fluid on T2 and T2* weighted images. Volume acquisitions often result in lengthy scan times and it is quite common for patients to move during this time. Immobilization with pads, and informing the patient of the necessity to keep still, are therefore very important.

Patient considerations

Patients with metal screws or prostheses may experience some discomfort. The patient should be warned to inform the operator if this occurs. Some patients may be unable to extend their knee and place it within the extremity coil. In these cases a flexible coil wrapped around the knee or a pair of coils placed lateral and medial to the knee, linked together or as a phased array, are often sufficient. Splints and braces should be removed before the examination.

14

Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

IV contrast is virtually never indicated in knee joint imaging although it may assist in the classification of some pathologies. MR arthrography is used for the diagnosis of meniscal tears and chondral defects and for identifying residual or recurrent tears in the knee following meniscectomy. It also has a role in identifying loose bodies within the joint. A very dilute solution of gadolinium in saline (1 : 100) is introduced into the joint capsule and the single joint is imaged at high resolution with fat-suppressed T1 weighted images in three planes aligned relative to the joint as described.

Tibia and fibula

Basic anatomy (Figure 14.20)
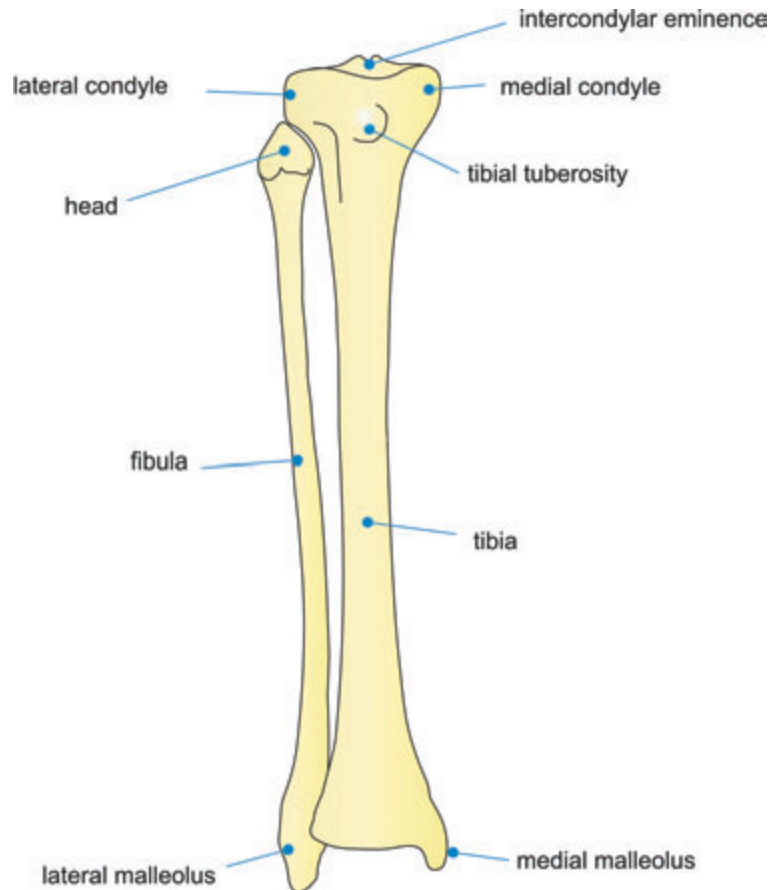
Figure 14.20 Anterior view of the right tibia and fibula.

Common indications

- Assessment of suspected or known pathology of soft tissues and bone (tumours, infection, muscle tears). A bilateral examination is recommended for all new cases, but single-sided imaging can be used for follow-up examinations, particularly if an array coil is not available.

Equipment

- Body array coil for imaging both or one leg/body coil for both legs/long surface coil placed under the leg (if only one leg is under examination and the ROI is localized posteriorly in the calf).

14

- Immobilization pads and straps.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with their legs straight and their feet in a comfortable position. The feet are immobilized in this position using pads and straps. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the knee and the ankle (or over the ROI if this is known). If a rectangular/asymmetric FOV is utilized in subsequent imaging, the vertical alignment light lies midway between the posterior and anterior surfaces of the lower leg. If only one side is to be imaged, the patient should be moved until the leg is as close as possible to the midline of the bore. Use the plastic ruler to measure from the transverse alignment mark to the joints to ensure the full length of the leg will fit within the long axis of the FOV. If not, include either the knee or ankle depending on the location of the lesion(s). When a lesion is palpable, place an oil- or water-filled marker over it. For large lumps or scars place a marker at each end.

Suggested protocol

Axial/multiplanar SE/FSE/incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. The axial plane locates the tibia and fibula in the AP direction but does not indicate if the full length of the tibia will be included on the next series. Coronal images are required for this and may substitute the axial (see below). Medium slices/gap are prescribed on the other side of the horizontal alignment light.

Axial localizer: I 50 mm to S 50 mm

Coronal SE/FSE/incoherent (spoiled) GRE T1

Locates lesions in the RL axis and may be used as a localizer, or a diagnostic sequence. Medium slices/gap are prescribed relative to the vertical alignment light from the posterior to the anterior aspects of the lower leg(s) or tibia and fibula. The whole of the tibia and fibula from the ankle to the knee is included in the image.

Coronal localizer: P 50 mm to A 20 mm

Coronal/sagittal STIR

Medium slices/gap are positioned and orientated along the line of the leg so that the whole of the tibia and fibula from the ankle to the knee is included in the image. If bilateral lesions are suspected, scan both legs.

14

Coronal SE/FSE T1

Medium slices/gap are prescribed and orientated along the line of the leg from the back to the front of the calf. The whole of the tibia from knee to ankle should be included in the image. Both legs should be examined to enable comparison and to identify lesions located in the marrow space.

Axial SE/FSE T1

Medium slices/gap are prescribed to extend well above and below lesions seen in the sagittal and coronal planes. Axial images are useful to localize lesions within significant anatomical compartments. Breach of the marrow space, extension within or through muscle compartments, and association with the neurovascular bundle are all significant characteristics.

Axial FSE T2 +/– chemical/spectral presaturation

Slice prescription as for Axial T1.

Image optimization

Technical issues

The inherent contrast is relatively good in this area due to the apposition of muscle and fat. Medium slices and resolution, combined with sensitive coils, allow a fast examination with the potential for higher-resolution images if required. A surface coil substantially increases the signal compared with the body coil, but signal fall-off in the anterior part of the leg sometimes prohibits its use. Whenever a tumour is suspected, the entire leg must be examined to ensure that additional skip lesions are detected. This can be achieved with the body coil or by offsetting the top and bottom parts of the body array coil. Good spatial resolution is achievable, especially if FSE is used, as fine matrices can be selected without unduly lengthening the scan time.

   When imaging a single leg, a rectangular/asymmetric FOV is used effectively in the coronal and sagittal planes with the long axis of the rectangle parallel to the long axis of the tibia and fibula. In axial imaging of both legs, a rectangular/asymmetric FOV can be used with the long axis of the rectangle R to L. Ensure that the legs are raised so that the vertical alignment light passes through the middle of the lower leg in the vertical axis. In this way, both tibiae and fibulae are included in the image. This strategy is not essential if the rectangular/asymmetric FOV can be offset or if a variable FOV is available, as with these options the size of the FOV along the shorter, phase axis can be extended to include all anatomy. On FSE T2 weighted images signal from fat remains bright, so that fat-suppression techniques are often helpful to distinguish fat from pathology. When utilizing chemical/spectral presaturation techniques a reduced bandwidth increases the SNR considerably and should therefore be employed when

14

possible. Additional shimming may be required before chemical/spectral presaturation sequences.

Artefact problems

Phase artefact originates from flow motion in the popliteal and posterior tibial arteries and saphenous veins. Spatial presaturation pulses placed S and I to the imaging volume reduce this effectively. On axial FSE and sagittal imaging, however, flow artefact is often troublesome. GMN minimizes the problem although, as it also increases the signal from vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences.

Chemical shift artefact must be kept within one pixel, particularly in axial images, to clearly delineate the interface of marrow and cortical bone and the edges of muscle compartments. Fat-suppression techniques are commonly used, especially in FSE T2 weighted images where the signal from fat remains bright and may return a similar signal to pathology. In T2 FSE, the signal returned from muscle is usually lower in FSE than in SE imaging, thereby increasing conspicuity of some lesions. To enable accurate characterization of a new lesion, MRI must be performed before tissue biopsy or partial excision.

Patient considerations

Patients should be immobilized adequately to avoid motion artefact. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely used in the tibia and fibula. It may, however, be useful for tissue characterization of certain tumours.

14

Ankle

Basic anatomy (Figure 14.21)
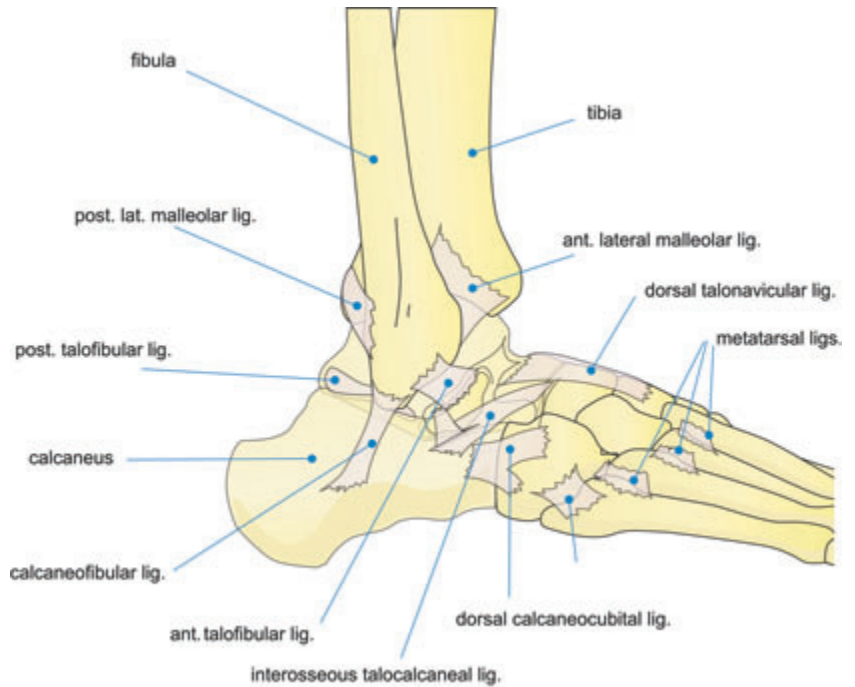
Figure 14.21 Sagittal view of the foot and ankle showing ligaments on the lateral aspect.

Common indications

- Assessment of ankle pain of unknown cause.
- Tendonitis (especially posterior tibial).
- Exclusion of osteochondritis dissecans.
- Achilles tendon rupture or tear.
- Avascular necrosis of the talus.
- Evaluation of the ankle joint following trauma.
- Soft tissue abnormalities.
- Possibly useful for evaluation of lateral ligament complex.

Equipment

- Knee phased array coil/extremity coil/pair of small circular coils combined as a multi-array/flexible coil.
- Immobilization pads and straps.
- Ear plugs.

14

Patient positioning

The patient lies supine on the examination couch with their foot and ankle within the coil. The foot is dorsiflexed so that the dorsal aspect of the foot is perpendicular to the examination couch and it is immobilized in this position with pads. The foot and ankle can also be raised so that the vertical alignment light lies at the level of the malleoli. This ensures that the ankle is at isocentre along the vertical axis. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the malleoli that corresponds to the centre of the coil. The other foot is usually placed next to the coil and immobilized with pads and straps.

Suggested protocol

Sagittal/Multiplanar SE/FSE/incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable or, if the ankle has been centred correctly, as a diagnostic sequence. Medium slices/gap (thin slices necessary for Achilles tendon) are prescribed on either side of the longitudinal alignment light, from the lateral to the medial aspects of the ankle. The area from the inferior border of the calcaneum to the distal portion of the tibia is included in the image. The sagittal plane enables correct positioning of AP and SI offsets.

Sagittal localizer: L 25 mm to R 25 mm

Axial SE T1

Thin slices/gap are prescribed to include from the origin of the Achilles tendon to the bottom of the calcaneum, and may require two sequences to provide adequate coverage (Figure 14.22). This sequence provides a clear anatomical display of the tendons of the ankle as well as the vasculature, nerves, and musculature. SE sequences are preferred for evaluating tendon damage as FSE sequences mix early and later echoes and, therefore, make it difficult to distinguish tendonitis from partial tears.

Axial FSE PD/T2 +/– chemical/spectral presaturation

Slice prescription as for Axial T1.
   This sequence is useful to classify tendon injury and identify joint effusions. Chemical/spectral presaturation techniques often demonstrate subtle trabecular damage and cartilage.

Sagittal SE/FSE T1/PD (Figure 14.23)

Thin slices/gap are prescribed from the lateral to medial aspects of the ankle. The whole of the foot and ankle from the sole of the foot to the

14

Figure 14.22 Sagittal PD weighted image showing slice prescription boundaries and orientation for axial imaging of the ankle.
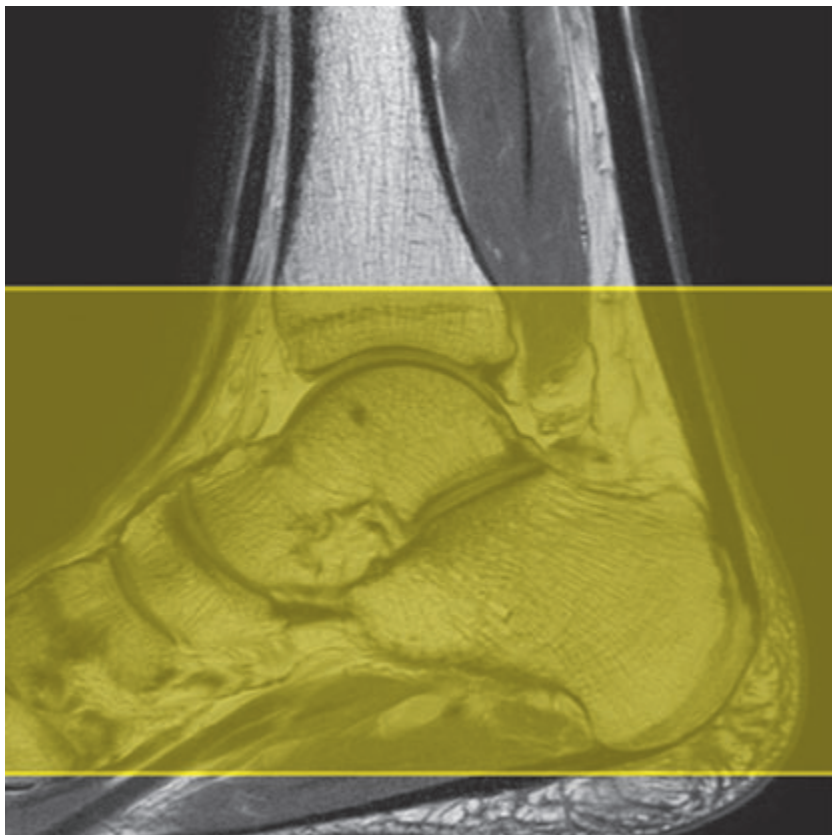
Figure 14.23 Sagittal PD weighted image with chemical presaturation.

14
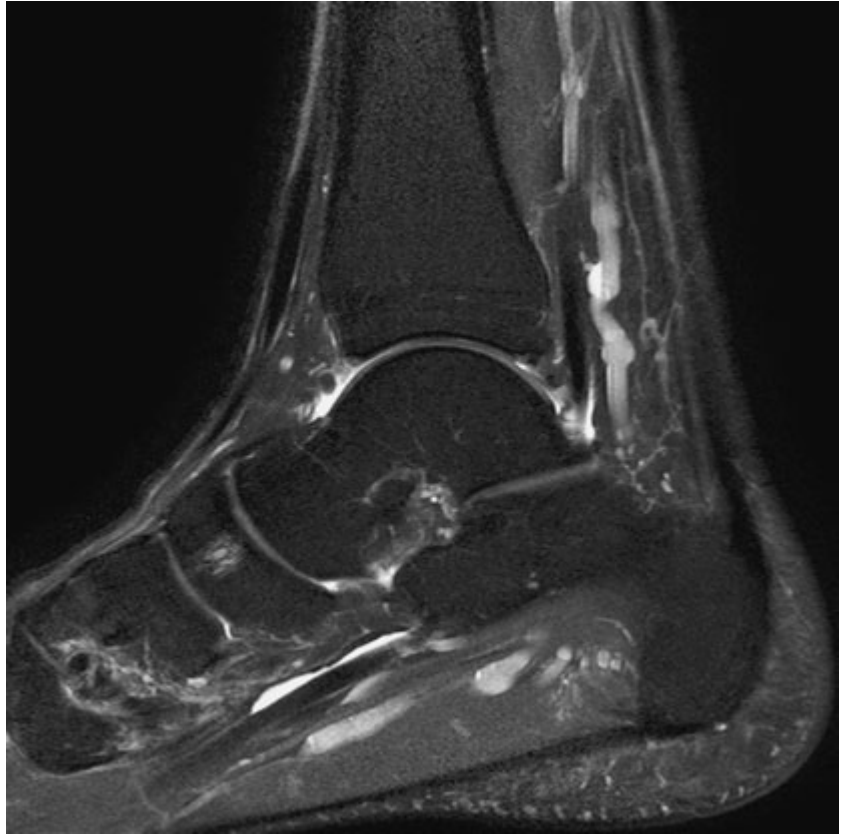
Figure 14.24 Sagittal FSE T2 weighted image of the ankle.

distal tibia is included in the image. This sequence is necessary to visualize the tendons and permit assessment of the bony components of the ankle.

Sagittal FSE/coherent GRE T2/T2* +/– chemical/spectral presaturation or STIR (Figure 14.24)

Slice prescription as for Sagittal T1.

Demonstrates joint effusion tendonopathy and calcaneal or tarsal fractures.

Coronal SE T1 or FSE PD/T2 +/– chemical/spectral presaturation (Figure 14.26)

Thin slices/gap are prescribed from the Achilles tendon to the base of the proximal metatarsals (Figure 14.25). This sequence demonstrates the collateral ligaments and can be extended into the foot to visualize the distal portions of the posterior tibialis tendon. T1 weighting is preferred for tendon injuries or chronic pain. The dual echo sequence is useful for acute injuries and suspected osteochondral defects.

14

Figure 14.25 Sagittal PD weighted image showing slice prescription boundaries and orientation for coronal imaging of the ankle.

14
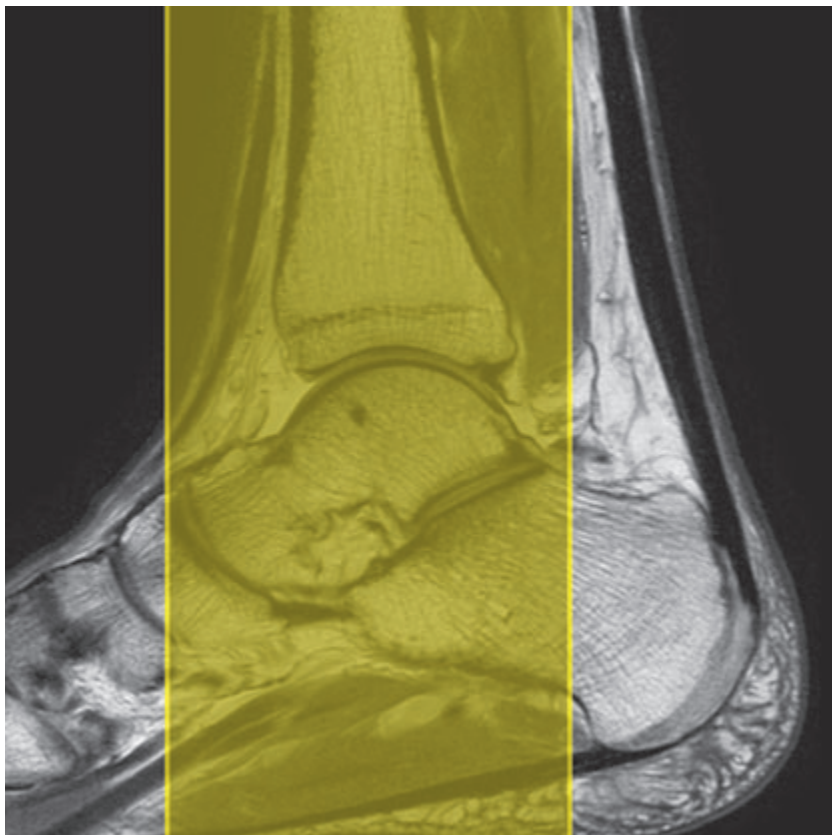
Figure 14.26 Coronal FSE PD weighted image of the ankle.

Figure 14.27 High-resolution sagittal incoherent (spoiled) T1 weighted image of the ankle.

Additional sequences

3D incoherent (spoiled)/coherent GRE T1/PD/T2* (Figure 14.27)

Thin slices and a medium number of slice locations are prescribed through the joint, from above the distal tibia to below the sole of the foot.

Fast incoherent/coherent GRE/SS-FSE/GRE-EPI/SE-EPI

For dynamic imaging of the ankle to assess subluxation and other injuries.

Image optimization

Technical issues

The SNR in the ankle is usually high, mainly due to the design of most coils. These are often transmit and receive coils and therefore ensure

optimum and uniform signal coverage. In addition, the muscle, fluid and fat components of the ankle give good inherent contrast. Excellent spatial resolution is usually necessary, especially when examining small structures such as the Achilles tendon. Therefore thin/medium slices/gap and fine matrices are required.

A 3D acquisition with an isotropic dataset is useful to provide high-resolution visualization of anatomy in any plane. A PD weighted coherent GRE sequence is most typically employed. Dual GRE sequences provide the same weighting but with additional high signal from fluid which demonstrates joint effusions and provides good contrast with the articular cartilage. They are therefore preferred for injured joints. An AP phase encoding axis permits the use of a rectangular/asymmetric FOV to reduce scan times.

Artefact problems

The main source of artefact is from the posterior tibial vessels. Spatial presaturation pulses placed S and I to the FOV are efficient at reducing this. Aliasing from the toes that are situated within the coil but outside the FOV may obscure relevant anatomy in sagittal imaging. Spatial presaturation pulses placed A to the FOV or oversampling reduce this problem. GMN further minimizes flow artefact but, as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1 weighted sequences. However, it effectively increases the contrast of the synovial fluid in T2 and T2* weighted images. Additional shimming may be required before chemical/spectral presaturation sequences.

Patient considerations

Patients with metal screws or prostheses may experience some discomfort. The patient should be warned to inform the operator if this occurs. Splints and braces are removed before the examination. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

IV contrast is not used to assess joint disease although it may be useful for the classification of tumours. Direct MR arthrography is sometimes used in the ankle to identify ligament tears and for increasing the sensitivity for ankle impingement syndromes. It also has a role in assessing the stability of osteochondral lesions and delineating loose bodies.

14

Foot

Basic anatomy (Figure 14.28)

Figure 14.28 Bony structures of the foot.

Common indications

- Evaluation of bony and soft tissue abnormalities (tumour, infection).
- Diagnosis of bone trauma not seen with conventional radiography.
- Bony tumours.
- Tarsal coalitions.

Equipment

- Extremity coil/head coil/flexible surface coils/small coil configured as a multi-coil array.
- Foam immobilization pads and straps.
- Ear plugs.

Patient positioning

Due to the non-orthogonal axis of the feet, true coronal and sagittal imaging can be difficult to obtain without oblique scan prescription. With the feet dorsiflexed, true sagittal imaging is possible, but due to the curvature of the tarsal bones, coronal imaging is sometimes difficult. It is probably advisable to examine the patient as for an ankle if the tarsal bones are the ROI, and reserve specific imaging of the foot if the toes and metatarsals are under investigation. The patient is usually positioned as for an ankle in the extremity or head coil. When using these coils ensure that the toes do not protrude beyond the coil anteriorly. This may happen if the patient has large feet and, under these circumstances, a surface coil is required to provide adequate coverage. The forefoot can be examined effectively and comfortably using a flexible surface coil or a two-coil array with the patient prone and the foot plantar-flexed. Immobilization of the foot and the coil using crossed straps and sponges is essential in both cases.

If the prone position is used, raise the foot and coil so that the long axis of the foot is at the level of the horizontal alignment light. If the feet are flat down on the surface coil, raise the coil and foot so that the vertical alignment light lies through the middle of the foot in the vertical axis. This enhances patient comfort and ensures that every part of the foot is at isocentre, which simplifies subsequent imaging as no offsets are needed. The patient is made as comfortable as possible and immobilized with pads and straps if necessary.

Suggested protocol

Scan plane alignment

These protocols refer to the following anatomical planes. The axial plane is perpendicular to the long axis of the foot, showing the metatarsals in cross-section. A coronal plane is analogous to the AP X-ray view, with the metatarsals adjacent to each other.

Note: These planes may not coincide with terminology used in other texts and, depending on patient positioning, may not correspond to your scanner's orthogonal plane labelling.

Axial SE/FSE/incoherent(spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable so that the curvature of the tarsals and metatarsals can be evaluated. Medium slices/gap are prescribed on either side of the horizontal alignment light.

I 20 mm to S 20 mm

14

Axial SE/FSE T1

Thin slices/gap are prescribed to include from the end of the toes to the tarsal bones, with good resolution to provide a clear anatomical display
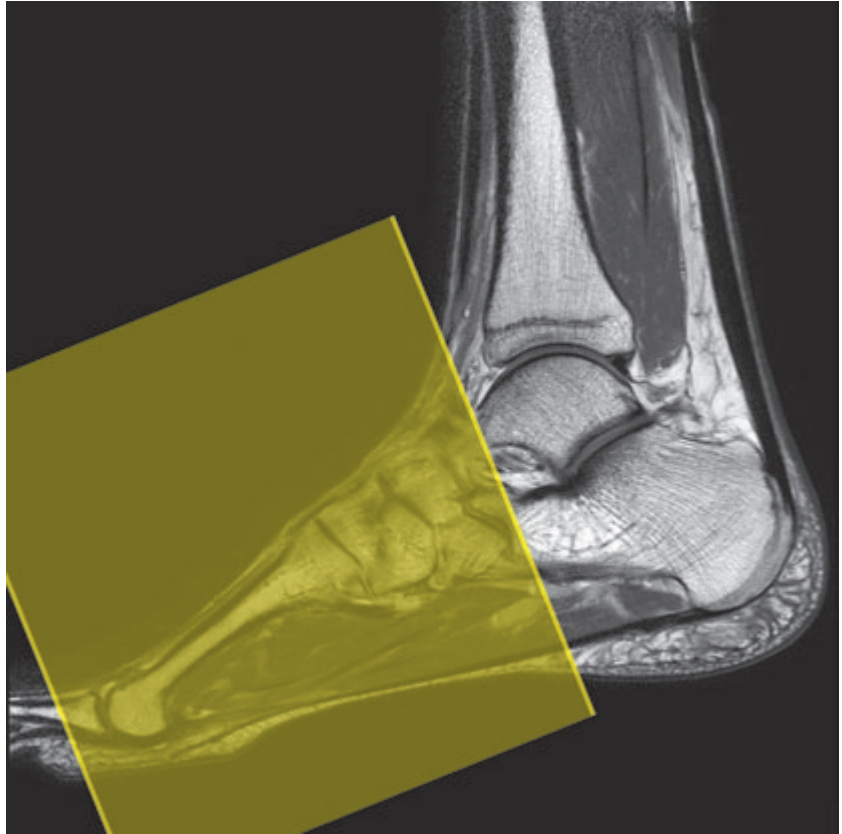
Figure 14.29 Sagittal FSE PD weighted image showing slice prescription boundaries and orientation for axial imaging of the foot.

of the anatomy of the foot (Figure 14.29). SE sequences are preferred for evaluating tendon damage but short ETL FSE sequences can be used to achieve higher spatial resolution in an acceptable scan time.

Axial FSE PD/T2 +/– chemical/spectral presaturation

Slice prescription as for Axial T1.

These sequences demonstrate joint effusions, mass lesions and collections. The addition of fat suppression enables visualization of subtle trabecular damage in stress fractures of the metatarsal bones.

Sagittal SE/FSE T1/PD (Figure 14.31)

Thin slices/gap are prescribed from the lateral to the medial aspects of the foot and should include the sole of the foot to the distal tibia (Figure 14.30).

Sagittal FSE PD/STIR/coherent GRE T2/T2* + chemical/spectral presaturation (Figure 14.32)

Slice prescription as for Sagittal T1.

14

Figure 14.30 Coronal FSE PD weighted localizer of the foot showing slice prescription boundaries and orientation for sagittal imaging of the foot.
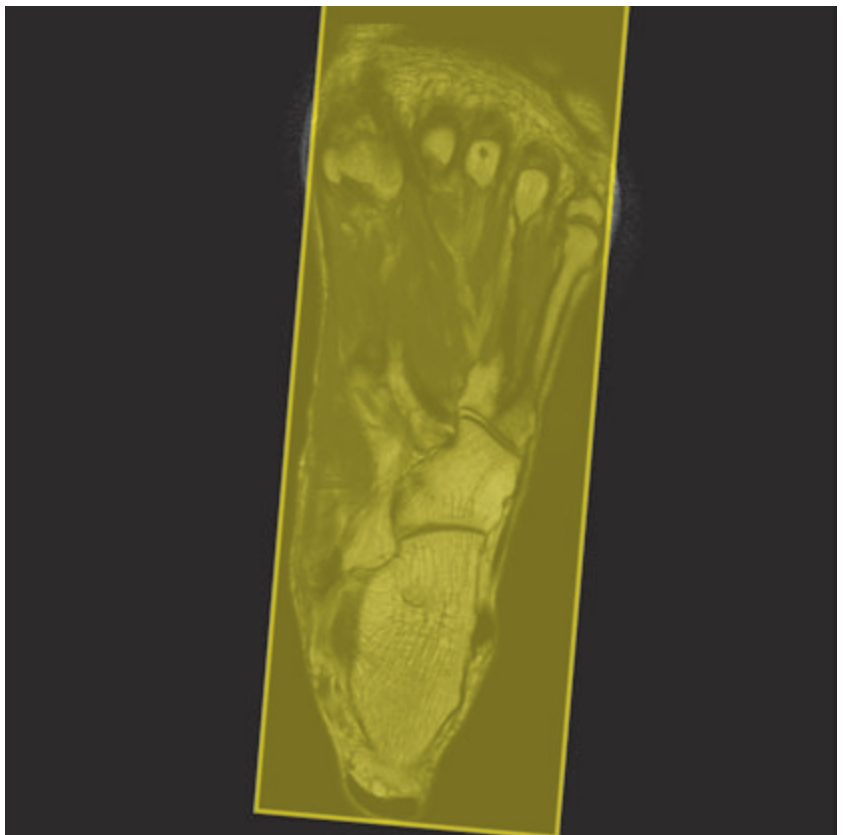
Figure 14.31 Sagittal FSE PD weighted image of the foot.

14

Figure 14.32 Sagittal FSE PD weighted image of the foot with chemical presaturation.

For demonstration of fluid collections, infection, and metatarsal or tarsal fractures.

Additional sequences

Coronal SE T1 or FSE PD/T2 + chemical/spectral presaturation

This scan plane is used in preference to the sagittal where the axial images show significant pathology extending between the metatarsal bones (Figure 14.33).

Sagittal 3D coherent GRE PD/T2*

Acquired as an isotropic dataset, this sequence may be useful to assess anatomy and pathology in any plane. Sagittal slices should include the whole of the foot from the sole to the distal tibia.

14
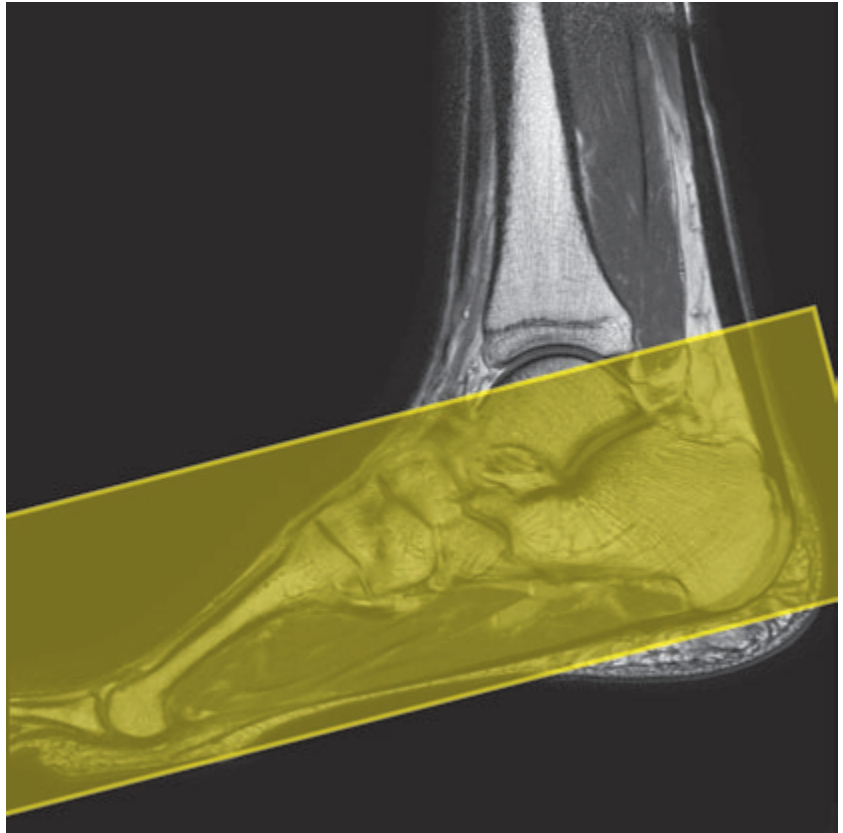
Figure 14.33 Sagittal FSE PD weighted image of the foot showing slice prescription boundaries and orientation for coronal imaging of the foot.

Image optimization

Technical issues

Foot imaging can be demanding as the foot is small compared with the available coils, compromising SNR and resolution. Flexible coils, simple arrays and dedicated coils can compensate for these inherent difficulties. Multiple NEX/NSA are often required to optimize the SNR. Excellent spatial resolution is necessary, especially when examining small structures such as the metatarsals and phalanges. Therefore thin slices/gap and fine matrices are required. Additional shimming may be required before chemical/spectral presaturation sequences.

14

Artefact problems

There is little flow artefact in this area but it is advisable to place a spatial presaturation pulse S to the FOV to reduce any flow originating in the distal vessels.

Patient considerations

Patients are carefully immobilized to reduce motion artefact. The position of the foot is important for subsequent imaging in orthogonal planes and the use of pads and tape to support the foot is advised. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely used in the foot.

Vascular imaging

Basic anatomy (Figures 14.34 and 14.35)

abdominal aorta

common iliac

internal iliac

lateral circumflex

femoral

popliteal

anterior tibial

posterior tibial

peroneal

dorsalis pedis
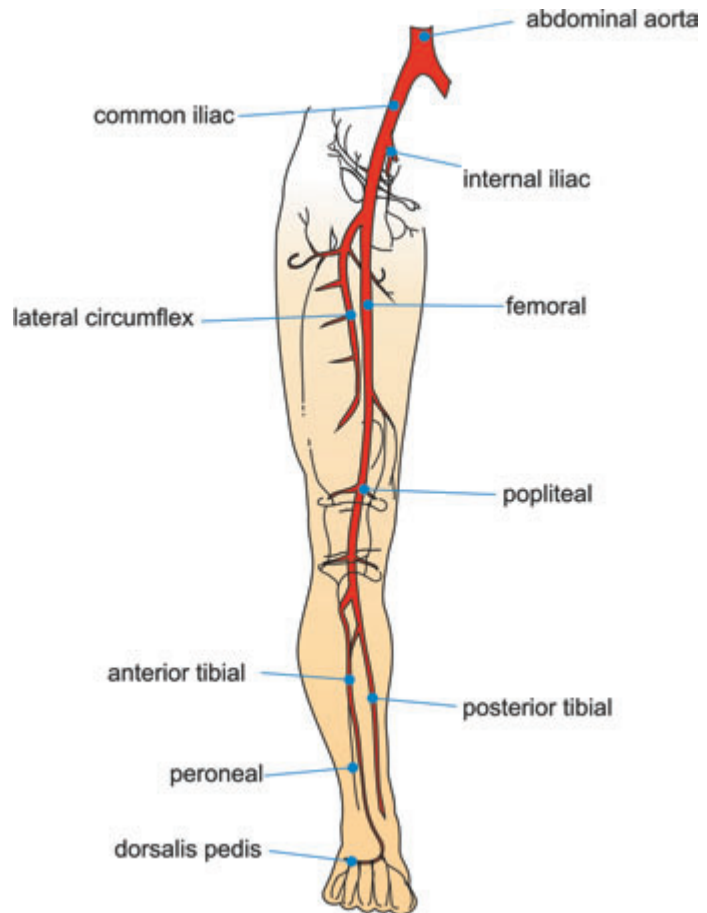
Figure 14.34 Vascular supply of the right leg.

Common indications

- Evaluation of peripheral vascular disease including stenosis and occlusion.
- Location of run-off vessels or site for arterial bypass of occlusion.
- Evaluation of normal venous vasculature (prior to coronary artery by-pass surgery to determine the optimal graft site).

It is essential to determine the objectives of the examination before commencing. For example, if the aim is to survey the entire peripheral

14
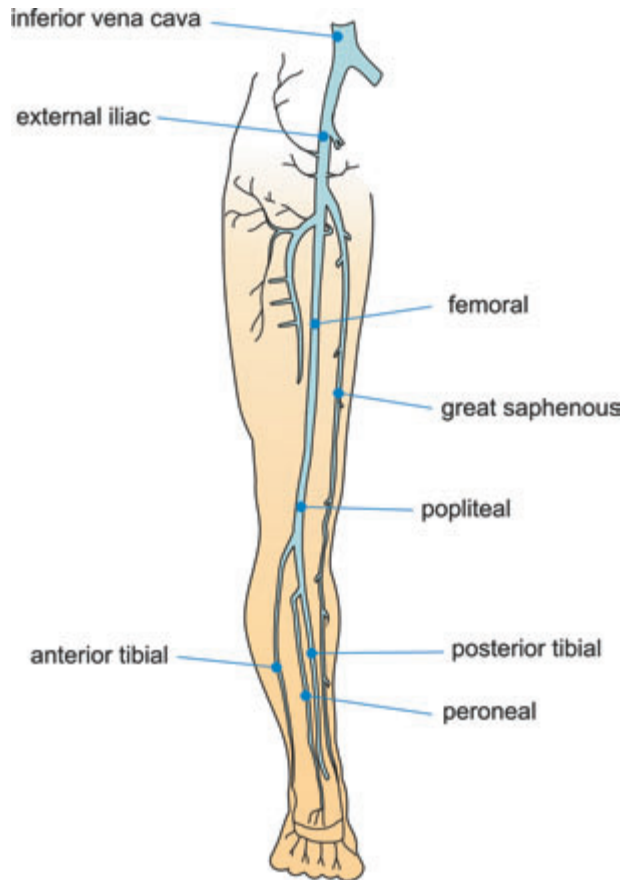
Figure 14.35 Venous drainage of the right leg.

vasculature, speed is more important than resolution and multiple FOVs, and sequences, adjusted to display arterial or venous flow, may be appropriate. However, if the aim is to find a tibial run-off vessel for grafting, the appropriate coils and techniques are different. The technique described here is for a full leg arteriogram. Use these key elements and your experience to develop more specialized techniques.

Equipment

- Body phased array/multi-coil array/surface coil/body coil.
- Immobilization pads and straps.
- Localization markers if required.
- Ear plugs.

Patient positioning

The patient lies supine on the examination couch with the legs extended into the magnet as far as possible. The legs and feet are immobilized using foam pads. Several series are acquired at different positions in the leg starting either at the feet or the pelvis. If the vasculature of the feet is important, place the feet flat down on to the coil and support this position with foam pads under the knees. This ensures that the vessels within the feet are perpendicular to the axial plane, which is necessary to optimize image contrast in TOF-MRA sequences. The patient then extends the legs again for imaging of the rest of the lower limb vasculature.

The patient is positioned so that the longitudinal light lies in the midline of the patient, and the horizontal alignment light is centred to the ROI. It is important to ensure that there is overlap between each series of images. Copper sulphate or oil markers may be taped on to the patient's lower limbs to achieve this or advance the table by 50 mm less than the longitudinal coverage of each set of sequences. Alternatively, when the first set of images has been acquired return the patient to the landmark position. Move the table to the location of the most superior slice in the imaging stack of the completed series. Mark this position on the patient using tape, and then reposition the coil so that this mark corresponds to the most distal end of the useful area of the coil. Landmark to the new centre of the coil ensuring that there is an overlap of at least 2.5 cm between each series. Switch to the body coil for imaging of the femora and pelvis.

Suggested protocol

Coronal incoherent GRE T1

Acts as a localizer if three-plane localization is unavailable. Use a large FOV to achieve maximum coverage. Medium slices/gap are prescribed on either side of the vertical alignment light.

<div align="right">

P 40 mm to A 40 mm

</div>

Axial 2D TOF-MRA

Developing a workable 2D TOF sequence for peripheral MRA is a complex task, as many conflicting factors must be taken into account. Most manufacturers provide suggested protocols optimized for their operational methods and post-processing software. It is probably advisable to start with these protocols and modify them when you completely understand the technique rather than start from scratch. Thin overlapping sequentially acquired GRE slices are obtained with a travelling spatial presaturation band positioned distal to the slice for arteriography, or proximal for venography. The slices are prescribed through the useful volume of the coil. It is vital to set the acquisition order to run against the direction of

14

Figure 14.36 Sequential CE-MRA of the iliac vessels showing an arterial venous malformation (first pass).

blood flow (e.g. from feet to head for leg arteries). Several series are performed moving the coil to a new location until the required vasculature has been visualized. There must be overlap between each series to avoid missing important pathology. The images are post-processed to provide oblique and AP views analogous to those collected in X-ray angiography (Figures 14.36–14.38).

Image optimization

Technical issues

The use of a good surface coil enhances the SNR in the lower leg. When utilizing the body coil to image the pelvis, the inherent SNR and CNR are generally adequate due to the use of a larger FOV. However, because of the length of the examination, a coarse matrix is often selected to try to minimize scan times, and resolution sometimes suffers as a result. To enhance vascular contrast, axial slices are selected so that the direction of flow is perpendicular to the slice. The use of GMN improves vessel

14

Figure 14.37 Sequential CE-MRA of the iliac vessels showing an arterial venous malformation (second pass).
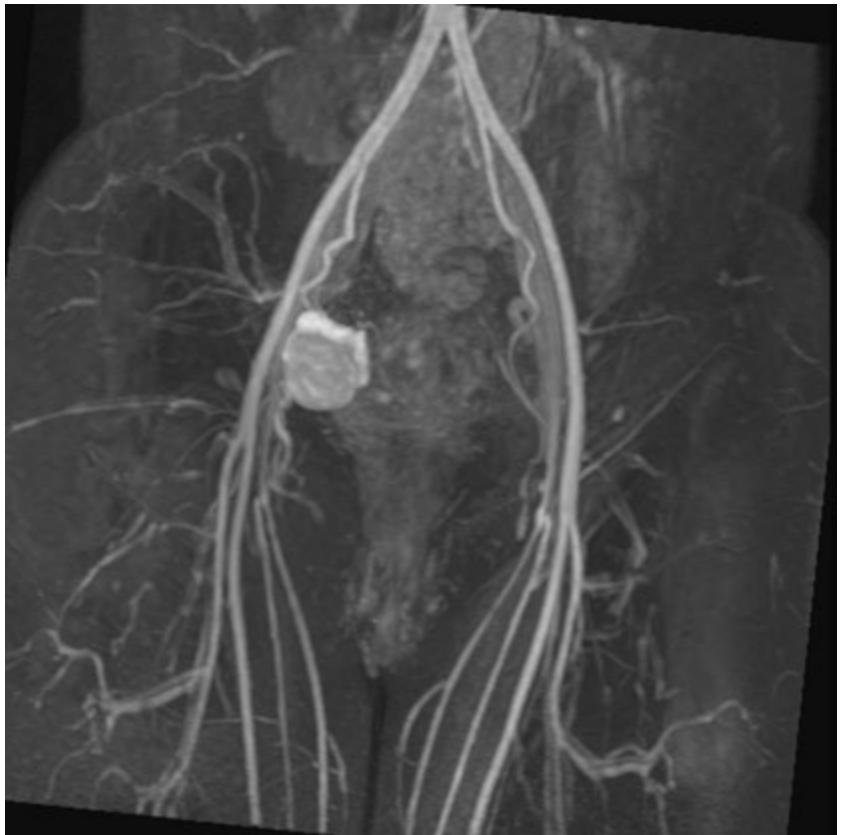
Figure 14.38 Sequential CE-MRA of the iliac vessels showing an arterial venous malformation (third pass).

14
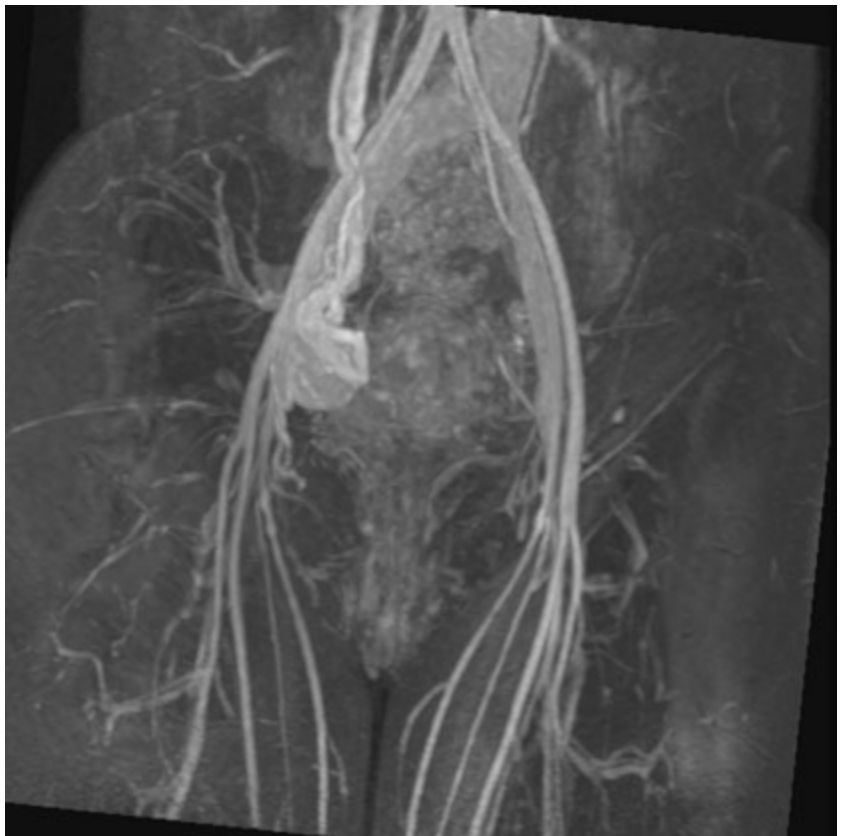
enhancement even further. MT is rarely used as it increases the relative signal of fat, which then interferes with the post-processed images. Travelling spatial presaturation bands placed between the origin of flow and the imaging stack nullify unwanted signal. These are placed S to the FOV to saturate arterial flow and demonstrate venous anatomy, and I to the FOV to saturate venous flow and demonstrate arterial anatomy. It is very important to locate the travelling presaturation bands correctly. Incorrect placement of these saturation bands leads to poor image quality and perhaps imaging of the wrong vessels.

ECG triggering can enhance the quality of peripheral 2D sequential TOF-MRA images by eliminating pulsatile flow ghosts and locking acquisition to the period of maximum distal flow rate. Flow is tri-phasic in peripheral vessels and will reverse direction through the cardiac phase.

Artefact problems

Motion of the body causes vessels to appear in different locations on sequential axial images and results in stepping in the post-processed images. Phase ghosting is also occasionally troublesome and is minimized by reducing the TE or using ECG triggered sequences. Fat signal is often inadequately suppressed during TOF-MRA sequences and may interfere with the image. Chemical/spectral presaturation pulses could reduce this unwanted signal but the time penalty is often unacceptable. Using a TE when the fat and water signals are out of phase with each other usually adequately suppresses background signal.

Vessel signal may appear to vary regularly along the line of a vessel creating a 'Venetian blind' artefact similar to that seen in large slab 3D TOF-MRA. However, in peripheral 2D TOF-MRA the mechanism for this appearance is quite different. It usually results from the travelling presaturation slab being too close to the scan plane. During the reversal of flow, blood slips back into the saturation band before being imaged. The same effect may result from blood upstream, which was imaged during previous slice acquisitions, flowing back into the current slice location. It also occurs if the slice acquisition order is not opposite to the direction of flow.

2D TOF-MRA sequences demonstrate reduced vessel signal where the vessel loops backwards or where there is a reversed flow direction. This latter situation is common distal to an arterial occlusion. Reverse flow in the distal limb of an occluded artery is provided from collateral supply but will not be shown with this technique. If the aim of the examination is to visualize the length of an occlusion accurately (e.g. consideration of angioplasty or surgical repair), PC-MRA, which is not flow direction sensitive, should be used.

14

Patient considerations

As the whole of the vasculature of the lower limb is imaged with an overlap of slices, the examination can take over one hour to perform. It

is therefore important to make patients as comfortable as possible and to warn them of the length of the study. It is wise to send the patient to the toilet before the examination begins! Ensure that the lower limbs are adequately immobilized, as any motion during the study causes artefact. Due to excessively loud gradient noise associated with some sequences, ear plugs must always be provided to prevent hearing impairment.

Contrast usage

A small dose of contrast (0.25–1 mmol/kg) shortens the T1 of blood and therefore increases the signal of flowing blood in TOF-MRA sequences. An extension of this technique, dynamic imaging after contrast, is now well accepted in examining peripheral vasculature. A range of approaches are under development with the required coils, sequences and coordination measures ranging from those that can be performed with most high-performance systems to those requiring extensive hardware and software modifications.

The technique is directly analogous to X-ray angiography. Extremely short TR sequences result in saturation of signal from most tissues except those with very short T1 times, such as the mixture of blood and gadolinium. In this way the vessel lumen is outlined. Short TEs (1–2 ms) are employed to minimize the effects of flow. Acquisition of the central portions of K space, relative to the IV injection, is timed to image the first pass of the contrast bolus through the arterial system. Subsequent acquisitions display the bolus in veins. 3D coronal GRE sequences with very short TRs and TEs are used with high-performance array coils. The coronal plane enables a fast sequence with large coverage, and images are then post-processed. A 'mask' scan is often acquired prior to injection for subtraction from the contrast images. This further reduces background signal and is essential if multiple injections are employed. Subtraction of the first pass arterial data from later acquisitions provides better isolation of the venous circulation. Timing of the scan to the bolus arrival is critical. This can be achieved with interactive scan initiation via navigator scans, by prior timing of a small dose in conjunction with a single location axial fast sequential scan, or by simple empirical estimation.

14

15 Paediatric imaging

Introduction

Paediatric MRI can be either an extremely enjoyable challenge or a technical nightmare. The unfamiliar surroundings, tunnel-like nature of the magnet bore, the loud gradient noise and the length of the examination may distress some children so that they are unable to cooperate fully with the examination. Refinements in magnet design such as larger diameter, shorter bores, acoustic dampening and more appealing outer coverings all help children and adults into the scanner. However, the commitment and training of staff and the culture of the department are probably the most important factors in the success of paediatric imaging. In many institutions paediatric patients are considered small adults but, in reality, this approach seldom produces quality imaging. This section discusses how to create the right environment for imaging the paediatric patient, the challenges associated with anaesthesia in the magnetic environment and the technical issues associated with MR examinations of children.

Creating the right environment

The paediatric population can range from a 400g neonate to an impressionable teenager, therefore patient approach must reflect an understanding of normal childhood development. The chance of obtaining quality diagnostic images is enhanced with accurate patient-specific information programmes. In a non-specialist paediatric unit the normal patient information documentation (written, verbal or computer based) is usually aimed at the mean socioeconomic level of the patient referral base, and will only be of limited use in the paediatric environment. Initially patient information should be targeted at school-aged children as they are more likely to absorb information than smaller children.

There are a multitude of effective processes available to assist children in coping with this potentially patient-unfriendly environment. This task is helped by obtaining advice from other health professionals who specialize in assisting children cope with a new environment (e.g. play specialists). The most successful programmes involve a combination of environment and pictorial, symbolic and verbal materials. The first step is to demystify

15

Table 15.1 Summary of parameters. The figures given are general and should be adjusted according to the system used (Table 2.1)

Spin echo (SE)

short TE	min to 30 ms
long TE	70 ms +
short TR	300−600 ms
long TR	2000 ms +

Fast spin echo (FSE)

short TE	min−20 ms
long TE	90 ms +
short TR	400−600 ms
long TR	4000 ms +
short ETL	2−6
long ETL	16 +

Inversion recovery (IR) T1

short TE	min−20 ms
long TR	3000 ms +
medium TI	200−600 ms
short ETL	2−6

STIR

long TE	60 ms +
long TR	3000 ms +
short TI	100−175 ms
long ETL	12−20

FLAIR

long TE	60 ms +
long TR	3000 ms +
long TI	1700−2200 ms
long ETL	12−20

Coherent GRE

long TE	15 ms +
short TR	≤ 50 ms
flip angle	20°−40°

Incoherent GRE

short TE	min−5 ms
short TR	≤ 50 ms
flip angle	20°−40°

Balanced GRE

TE	minimum
TR	minimum
flip angle	≥ 40°

SSFP

TE	minimum
TR	40−50 ms
flip angle	20°−40°

Slice thickness

2D	thin	2−4 mm
	medium	5−6 mm
	thick	8 mm
3D	thin	≤ 1 mm
	thick	≥ 3 mm

Slice numbers

Volumes	small	≤ 32
	medium	64
	large	≥ 128

Matrix (frequency × phase)

coarse	256 × 128 or 256 × 192
medium	256 × 256 or 512 × 256
fine	512 × 512
very fine	≥ 512 × 512

FOV

small	≤ 18 cm
medium	18−30 cm
large	≥ 30 cm

PC-MRA

2D and 3D	TE	minimum
	TR	25−33 ms
	flip angle	30°
VENC venous		20−40 cm/s
VENC arterial		60 cm/s

NEX/NSA

short	≤ 1
medium	2−3
multiple	≥ 4

TOF-MRA

2D	TE	minimum
	TR	28−45 ms
	flip angle	40°−60°
3D	TE	minimum
	TR	25−50 ms
	flip angle	20°−30°

15

the process by allowing patients to view the scanning environment prior to the appointment. This allows staff to make a decision about the level of support that will be necessary to help the patient cope with the examination. In addition, the appointment/patient screening form can be adapted into a colouring book with scan related cartoons that the children are encouraged to complete and return at the time of the appointment.

Familiarization with the scanning environment can be accomplished in several ways:

- Photographic or symbolic representation of the examination for the patient and family to read.
- Video: a step-by-step process from patient screening to examination completion.
- Computer based: this is an extension of the video system and, if available on the internet, can be accessed by the patient's family at any time.
- Involving play specialists or child psychologists to develop a de-sensitization process to help the children cope with their fears and apprehensions (e.g. a full-sized mock MRI unit, complete with scanning sounds, puppets with a small representation of the MR scanner and a calico doll. Children are encouraged to put the doll or puppet through the MRI process in a play setting).
- Develop a patient-friendly environment, e.g. child-related books, toys, videos and computer games in the waiting area greatly reduce a child's anxiety. Remove or cover anaesthetic equipment in the scan room. Shield certain patients from view (an intubated ICU patient does not breed confidence).
- Make the patient as comfortable as possible for the procedure and, importantly, talk to the child during the examination.
- Encourage them to bring a soft toy (MRI safe) to hold during the examination.
- Audio and video projection systems are available to entertain the patient during the procedure. Encourage the patient to bring their own tape or CD to listen to.
- Encourage a parent to accompany the child during the examination. (**Do not forget to screen the parent.**)

Finally, verbal reinforcement is probably the area that receives the least attention but has the greatest potential to help a patient get through an examination. This applies equally to the adult environment. The patient's initial impression will either create or break down barriers. Therefore:

- Talk **to** your patient, not **at** them.
- Bring yourself down to their level; look them in the face.
- Talk to them using terms that they can comprehend.
- Be confident in yourself; if you seem hesitant patients can sense this.
- Be friendly and talk about something that they seem interested in (sport, videos, computer games, latest music sensation, school, holidays, etc.). Develop a rapport.

15

- Tell them everything about the examination process; do not lie.
- Give positive reinforcement during all processes in the examination.

When examining a child, the process will inevitably involve one or more family member; therefore, the technologist must be prepared to explain the examination process to them. Listed below are the most common areas of concern that parents express about the MRI examination.

- Does the scan use radiation?
- What are the side effects of MRI?
- My child has had numerous other investigations, why do they need a MRI?
- Why do they have to hold still for so long?
- Why do they need an injection of contrast?
- What are the side effects of contrast?
- Can they continue their medication prior to the MRI?
- What are the fasting instructions for sedation/anaesthetic cases?
- Why do we have to complete such a long screening process?
- I am not having the scan, why do I need to complete the screening questionnaire?

When a child has already had numerous investigations and the role of MRI is to define the pathological process further, there can be a great deal of parental anxiety which can, if not handled correctly, have a detrimental effect on the child's cooperation. Your unit will be expected to have policies in place to deal with this situation if it arises. A parent who has confidence in the MRI staff can be a worthy ally in helping their child complete the examination.

Sedation and anaesthesia

Patients who are too young or too ill to cooperate will require some form of therapy to help them complete the MRI examination. Intervention of this kind requires careful consideration of the facilities available for sedation or anaesthesia. If your unit does perform these type of examinations, they must have policies in place to deal with the peculiarities associated with these types of examinations.

The primary goals of sedation or anaesthesia are:

- To control patient behaviour, especially movement.
- To minimize psychological disturbances and distress.

Staff considerations

The number of staff and the facilities available vary considerably. Some centres have a full nursing staff, admitting area and recovery room, whilst others may have none of the above. In addition, units attached to hospitals have wards and specialist doctors on site should any emergency arise, whilst isolated facilities have none of these luxuries. It is important that

15

the unit's policy towards sedation/general anaesthesia is discussed fully with the medical staff, and careful plans are made if sedation or anaesthesia is to be carried out in the unit.

There must always be a qualified doctor in the unit when a sedated patient is present. This doctor should take full responsibility for the patient and his or her condition, regardless of whether the doctor authorized the examination. The responsible physician must be easily located and aware that a sedated patient is present in the unit. Doctors on the telephone, teaching, or in a meeting are of no use in an emergency! Children can deteriorate very quickly and it is essential that time is not wasted looking for the radiologist or responsible physician.

It is preferable to employ nurses to supervise the sedation process. This ensures that the responsibility for sedating and monitoring these patients is undertaken appropriately, permitting the radiographer/MR technologist and administrative staff to perform their duties effectively. However, some units rely on ward nurses or radiographers to monitor patients, especially if the number of sedated patients is small. This is satisfactory as long as the appropriate personnel are trained and the physician also participates. All staff within the unit must be aware of the cardiac arrest/medical emergency procedure and should be regularly trained in cardiopulmonary resuscitation. Medical personnel should familiarize themselves on a regular basis with the emergency trolley, its equipment and drugs. Cardiac arrest teams must be fully aware of the location of the MR unit and be familiar with magnetic safety.

Facilities

If sedation is to be undertaken, there is ideally a quiet area away from the main waiting room where patients can recover undisturbed. However, this room must not be remote from the rest of the unit or personnel in case an emergency arises, and should contain a telephone or other means of communication. The parents are usually allowed to sit with their child during the recovery process so that the child is not alarmed when he or she awakes. This room is also useful for keeping the child in a quiet environment whilst the sedation takes effect. It is unreasonable to expect a child to fall asleep when telephones are ringing and people and patients are passing through the waiting area. If general anaesthesia is performed, there should be a separate anaesthetic room so that patients can be anaesthetized separately from recovering patients.

Equipment

An anaesthetic induction room adjacent to the MR system can be fully equipped with conventional apparatus and obviates the need for expensive alterations. It also allows other patients to be examined whilst anaesthetic induction is performed. There must be a fully equipped emergency trolley in this room that is checked regularly by the unit nurse, anaesthetic nurse, or other responsible party, on a weekly basis. The stocks of drugs used for

sedation and their antidotes must be regularly checked as must the anaesthetic trolley, accessories and induction agents. It is very important that any anaesthetic equipment taken into the magnet room is MR safe. If the equipment taken into the magnetic environment has a 'conditional' status the associated restrictions must be known and understood. Ideally there should be a piped supply of oxygen and nitrous oxide in the examination room, along with a vacuum for suction and gas scavenging. In the event that this is not possible alternative equipment must be available. In some centres the anaesthetic delivery system is located outside the magnetic environment and delivery of anaesthetic gases is via a long tube passed through a wave guide. This eliminates the need for an adapted magnetically safe anaesthetic machine. All other equipment such as endotracheal tubes and laryngeal masks must also be safe in the magnetic environment. If a breathing system is used it is necessary to ensure that this is not only magnetically safe, but is also long enough to pass into the magnet bore. Care must be taken to ensure that additional cables/monitoring lines have free access into the bore and will not hinder table movement in the event of an emergency.

Monitoring

The sedated/anaesthetized patient requires monitoring of vital signs before, during and after the MRI examination. There are many different vendors that supply equipment for the magnetic environment. Most of these have a 'conditional label', meaning that there will be restrictions on their use in an MR room. There are many types of MRI-compatible monitoring devices providing all levels of monitoring requirements. The most basic levels of sedation may only require basic pulse oximetry but some centres may also require capnography. Anaesthetized or critically ill patients require a more comprehensive level of monitoring (non-invasive blood pressure, invasive pressures, ECG, anaesthetic gases, etc.). It is, of course, vital that all monitoring equipment is at least labelled 'MR conditional'. If the equipment is strongly ferromagnetic, it may not only be attracted to the magnet but may also distort the magnet field and degrade image quality. Mechanical switches, cathode ray tubes and internal magnets do not function properly in the scan room and give false readings. In addition, the cables of the monitors act as antennae in the magnetic field and result in an interference pattern on the MR image. Therefore the requirements of monitoring introduce another variable into the safe MRI environment equation and, as such, there are several things that the MRI technologist must be aware of:

- As a minimum always use only MRI conditional equipment and accessories.
- MRI conditional is different from MRI safe.
- If required, prior to accepting equipment check that it has been certified by the local statutory body, e.g. the FDA, the Medical Devices Agency.

15

- Check that all components match the model number listed by the manufacturer as MRI conditional or safe.
- Be aware of any MR conditional requirements of equipment taken into the scan room.
- Get the system electrically tested by the local biomedical unit.
- Use hand magnets to test various components (casing, stand, etc.) to see if they are ferromagnetic.
- On phantom or volunteer studies test individual sequences for artefacts.
- Read the manual for safe operating technique.
- Run in-service lectures so that the different levels of staff understand the basic functions of the system.
- Regularly inspect cables for signs of damage.
- Research carefully before buying.
- If you suspect any component of the monitoring system has caused an injury to the patient immediately remove it from service. Contact the manufacturer/service agent to get the problem rectified.

Remember: MRI conditional is different from MRI safe

Placing equipment outside the room and passing monitoring cables through an RF filter within the penetration panel may diminish image quality and induce artefacts. Fibre-optic cables will reduce interference and a liquid-crystal display, instead of a cathode-ray tube, eliminates the distortion problem of conventional ECG monitors. When purchasing MR monitoring equipment be aware of the conditional aspects of the equipment. Some systems are purpose built, whereas others may involve conventional equipment enclosed in a Faraday shield. It should be noted that many MRI vendors specifically prohibit the use of the gating equipment for monitoring purposes during sedation/general anaesthesia. They state that the monitor is not designed for accuracy under these circumstances and is therefore unreliable. Check the manufacturers' specifications for details.

Patient preparation

The patient admission policy of the unit often varies according to facilities available and whether sedation or general anaesthesia is to be administered. If the child is to be sedated in the unit, he or she must arrive at least two hours before the examination. This allows for all the admitting procedures to be completed, for sedation to be given, and for it to take effect. Some facilities attached to a hospital may wish to admit the child on to a day ward. Although this alleviates the problem of children and parents cluttering up the waiting area, it entails the cooperation of ward nurses and porters. Large units, which have separate waiting areas, sedation rooms and recovery areas incorporated into the building, often find admittance to a ward unnecessary.

Each child has a full medical assessment by a paediatrician, paediatric radiologist, sedation nurse or anaesthetist before the examination. This

15

includes allergies to medicines, current medication, previous and existing medical problems and a note of the patient's vital signs. All tests, such as blood tests and X-rays, are completed and the results accepted as satisfactory by the admitting doctor. The drugs required for the sedation/general anaesthesia are written in the notes by the admitting doctor or anaesthetist, and consent for sedation or anaesthesia acquired from the parents. Once the child arrives at the centre the vital signs are checked and recorded. The child's clothing should be checked for examination suitability and, if necessary, they should be changed into hospital pyjamas. Gowns may be used but pyjamas are likely to be warmer. A full magnetic screening of the parents, child and accompanying nurse must be carried out.

It is the responsibility of the MRI unit and the referring physician to ensure that adequate pre-examination fasting has occurred. This differs depending upon the age of the patient involved. The fasting schedule given to the parents or ward staff must contain clear and concise instructions, information about continuing any medications and the phone number of a contact person for clarification. It should be noted that in some centres fasting instructions may vary depending upon the type of sedation administered. An example of a fasting schedule is listed below:

IV and gaseous sedation agents

- 0–12 months: Patient may have solids and milk up to 4 hours (breast milk 2 hours) before the scheduled examination. Clear fluids may be given 2 hours before the examination.
- 2 months–4 years: Patient may have solids and milk up to 4 hours (breast milk 3 hours) before the scheduled examination. Clear fluids may be given 2 hours before the examination.
- 4 years plus: Patient may have solids and milk up to 6 hours before the scheduled examination. Clear fluids may be given 2 hours before the examination.

Oral sedation (all ages)

- 2 hours solids and fluids.

Some centres elect to perform MRI examinations on small babies by feeding them and swaddling them so that they feel warm and secure, however there is a chance of vomiting and aspiration so the infant must be carefully watched at all times.

Venous access is required for some forms of sedation and most general anaesthetics. In addition it is required if contrast is used. Many children and adults are frightened of or apprehensive about injections. An easy approach is to use vasodilating topical local anaesthetic creams which, in some circumstances, may be vasoconstrictive, and should be removed at least 10 minutes before cannulation. In cases where there is uncertainty as to whether contrast agents are required, use topical anaesthetic cream anyway. It is easier to remove the cream if an injection is not required

15

than upset the child. Haematology/Oncology patients with infusions may prefer to have these accessed for contrast administration. This can be time-consuming but avoids difficult venous access. The access of central infusion lines requires knowledge of sterile procedures, access techniques and the correct type of heparin lock. If your unit does not have a policy regarding accessing central lines, contact the referring Haematology/Oncology Unit.

Sedation/anaesthesia strategies

There are two therapies available:

- Sedation: Produced by the administration of drugs or combination of drugs which depress the level of consciousness while retaining the ability to maintain a patent airway. Adequate respiratory drive is maintained and the patient responds to verbal stimuli. This form of sedation can be administered intravenously, orally, intranasally, per rectum or intramuscularly. The route of administration will depend upon the type of drug, experience of the staff and the patient. All types of sedation can potentially produce general anaesthesia.
- Anaesthesia: Refers to a state of depressed consciousness from which the patient is not arousable and in which partial or complete loss of protective reflexes, including the ability to maintain a patent airway, may occur and in which purposeful response to verbal or physical stimuli will not occur. Normal respiratory drive may also be lost.

In many centres that perform large numbers of sedations there is a preference for physician/nurse led sedation units. The preference for these types of units is often based upon economic reasoning combined with an experienced group of nurses. The type of sedation offered to patients will reflect regulatory and hospital based protocols. The pharmacological cocktails offered as sedation in some units may be considered anaesthesia in others. The success of any nurse led programme is stringent policy decisions and direction, coupled with accurate assessment of patients.

The use of consistent terminology and grading of patients is a crucial factor in determining management of the sedated patient. The University of Michigan Sedation Score (UMSS), which describes the level of sedation, is sometimes used. This comprises the following:

Minimal sedation – (anxiolysis) – Sedation score 1

- A drug-induced state during which patients may respond normally to verbal commands.
- Cognitive function and co-ordination may be affected.
- Respiratory and cardiovascular functions are minimally affected.

Moderate sedation ('conscious sedation') – Sedation score 2

- A drug-induced state of depressed consciousness with preserved airway protective reflexes.

15

- Patients may be somnolent/sleeping but easily aroused with light tactile stimulation or verbal command.

It is possible for patients to progress from a state of moderate sedation into a deep sedation/obtundation **very easily.**

Deep sedation – Sedation score 3

- A drug-induced state of depressed consciousness from which the patient is not easily roused.
- Sedation may be accompanied by partial or complete loss of protective airway reflexes.
- Patients are usually unable to respond purposefully to physical or verbal stimulation.

There are some contraindications to sedation techniques and some of these are listed below:

- Increased risk of delayed gastric emptying or vomiting.
- Significant respiratory disease.
- Abnormal conscious state or raised ICP.
- Previous adverse event with sedation.
- Acute systemic illness.
- Patient currently receiving opioids or other sedative agents.
- Age related requirements – oral vs. IV.

The safe conduct of anaesthesia requires a trained anaesthetist and dedicated assistant, as well as specialist equipment, which may require expensive modification to be magnetically safe. The anaesthetist and other anaesthetic staff must be experienced and knowledgeable of the hazards of the magnetic field. It is preferable that they attend the unit on a regular basis so that MR practitioners do not have repeatedly to educate and screen new anaesthetists. In the interests of magnetic safety, anaesthesia may be induced in a separate room and once the patient's airway is secured, he or she is then transferred to the scan room. Alternatively they can be anaesthetized in the scan room under strict supervision.

It is important that a minimum amount of equipment is taken into the scan room. All anaesthetic equipment deemed MRI safe/conditional should have a distinctive colour coding or be labelling to reduce the possibilities of unsafe accessories entering the vicinity of the magnet environment. In units performing a large number of anaesthetics it is possible, once strict guidelines have been established, to perform minor procedures such as lumbar punctures or skin biopsies within the magnet environment.

Always double check the patient, anaesthetist and anaesthetic accessories for ferromagnetic objects before entering the magnetic field.

The anaesthetist may choose to maintain anaesthesia with inhalation agents that then require scavenging to the atmosphere, or by IV anaesthetics that require infusion pumps. These pumps not only present a projectile

15

risk and may induce RF artefacts, but the unit may malfunction in the magnetic field. To avoid problems of this nature, infusion pumps are placed as far away from the magnet as possible, or the agents are infused by hand. The patient is either allowed to breathe spontaneously or they have their lungs mechanically ventilated. Breathing systems are required that are long enough to pass into the magnet bore. The airway is secured either by endotracheal intubation or by a laryngeal mask. The most common method is probably the laryngeal mask technique but this has several drawbacks as far as the MR examination is concerned. A large amount of air is often used to inflate the mask, which creates a susceptibility interface especially in GRE, chemical/spectral presaturation and EPI sequences. In addition, the valve used to maintain the cuff may contain a small spring, which can fall into the imaging volume, causing an artefact. However, these problems can be overcome by consulting the anaesthetist prior to the examination.

The type of therapy chosen will depend on many factors including:

- Age and size of the patient.
- Type of MRI to be obtained.
- Patient's physical condition.
- Availability of anaesthetic staff.
- Support personnel in the event of an unanticipated clinical event.
- Monitoring and anaesthetic equipment.
- Location of the MRI unit (outpatient or hospital facility).

There are advantages and disadvantages of both sedation and anaesthesia. The decision to use one or the other is made by the referring clinician, radiologist and anaesthetist. With the increased popularity of many breath-hold techniques for cardiac and abdominal imaging, the need for respiratory control may expand. The following should be taken into consideration.

Advantages of anaesthesia over sedation

- The time that unconsciousness is achieved is predictable so there is little disruption to the schedule.
- It is safe to assume that the patient will remain asleep during the entire examination and not wake up due to the gradient noise or the sedation wearing off.
- As the anaesthetist usually inserts an IV line, there is access for the administration of contrast or emergency drugs.
- There is a trained anaesthetist present during the examination and recovery period should an emergency arise.
- If an endotracheal or laryngeal mask is inserted the airway is secured.
- Patients often wake up faster from a carefully balanced anaesthetic than they do from sedation and so the patient can leave the unit sooner.

15

Disadvantages of anaesthesia over sedation

- Requires an anaesthetist and anaesthetic nurse and is therefore costly.
- Requires magnetically safe anaesthetic equipment and involves a large capital outlay.
- The extra personnel and equipment increase the likelihood that there will be a breach of magnetic safety.
- It may be somewhat disruptive to the schedule, especially if several children are being anaesthetized in one session.
- Depending upon the type of anaesthetic there is an increased risk of post-examination vomiting.
- The children make become distressed after a light general anaesthesia as they become confused and disorientated when awakening.

Neonates and babies under 3 months

The younger the child, the greater is the chance that an unsedated examination will be successful. Particular care is necessary to keep these babies warm, as the bore fan and cool examination room can cause significant hypothermia. Swaddling the child in blankets usually provides sufficient insulation and also acts as a very effective immobilization device. Young babies and small children dissipate the majority of body heat from their heads. Ensure that the room and bore lights are dimmed prior to the patient's arrival, and that all personnel keep as quiet as possible during the examination. The child is monitored both with specific monitoring devices and by a parent, doctor, or nurse, present in the room. Particularly sick neonates require closer supervision. If an unsedated examination is unsuccessful, the baby is sedated as for older children.

Babies and children 6 months to 5 years

Children exhibit a variety of responses to sedation according to age, type of sedation used and the temperament of the child. Mentally disturbed and behaviourally challenged children are especially difficult to sedate effectively. Various sedation regimes have been described utilizing chloral hydrate (+/–liquid paracetamol), diazepam, pentobarbital or the Toronto mixture. Adult patients often respond well to IV increments of a short-acting benzodiazepine such as midazolam, which can be titrated to the desired effect. It is imperative that all sedated patients are monitored throughout the examination and recovery period. Oxygen should be provided via a face mask or nasal cannula. If sedation is ineffective, the doses of the above drugs can be increased under the guidance of a physician; however, as sedation is not always successful in this age group, anaesthesia is often required.

Children over 5 years

Children of this age can often be scanned without sedation. This depends largely on their age and level of maturity. The parents are very important

15

determining factors on the success of an unsedated examination. In some instances, calm parents are just as effective as a drug. However, there are some circumstances when sedation or anaesthesia is required.

Recovery

All patients who have been sedated or anaesthetized must have recovered fully before they are allowed to return to their home or to the ward. A patient is usually considered recovered if they are:

- Awake and orientated.
- Exhibiting stable vital signs for at least 1 hour after the end of the administration of anaesthesia.
- Able to tolerate oral fluids before leaving the unit or ward.
- In the company of a responsible adult.
- Do not have to operate machinery within 24 hours of the examination (adults only).

The parents are given easily interpretable verbal and written instructions to watch the child carefully and indications of typical behaviour in the next 24 hours. Contact telephone numbers in case of an emergency must be included in the instructions.

Emergencies

In the event of a patient requiring resuscitation during an examination (whether they have been anaesthetized or not), the cardiac arrest team is summoned. The patient should then be immediately evacuated out of the magnetic environment to the anaesthetic area. In this way emergency equipment is readily available and there is less risk of ferromagnetic items being inadvertently taken into the examination room. This manoeuvre also eliminates the necessity of screening all the personnel on the cardiac arrest team for magnetic safety. In addition, the unit staff should be regularly trained on the appropriate evacuation procedure and cardiopulmonary resuscitation.

Departmental policies

Taking on the responsibility of sedating or anaesthetizing patients requires departmental or unit-based policies to ensure as smooth a process as possible. These policies must include all aspects of the examination from scheduling of the patient to post-MRI follow-up. The key areas that should be addressed are:

- Patient selection criteria.
- Selection criteria for staff working with sedated or anaesthetized patients.
- Scheduling.
- Patient information regarding fasting instructions.

15

- Informed consent.
- Current medication.
- Pre-examination physicals.
- Type of therapy required.
- Reference to who can order and administer sedation/anaesthesia.
- Examination monitoring based on minimum accepted standards of anaesthetic department or association.
- Post-examination recovery period; essentials of vital-sign documentation.
- Unit follow up post examination
- Discharge information to parents.
- Unit follow-up and evaluation.
- Clear defined department protocols and procedures.

The MRI examination

Like adults, the majority of examinations in the paediatric environment are based on the neuroaxis (head and spine). In older children the examination technique is the same as for adults, but their concentration span may differ so later scans may exhibit some form of movement artefact. The greatest difference lies within the smaller, sedated or anaesthetized group where the examination may be terminated due to the patient waking up or to a change in the medical condition. As with any MRI examination, it is necessary to obtain the critical, high diagnostic yield scans early within the examination. One of the most common errors in performing paediatric examinations is to increase spatial resolution by reducing the FOV and slice thickness, without making the necessary adjustments to signal averaging to maintain SNR. In some clinical situations there may a problem with exceeding the currently acceptable SAR limits. This is more of an issue when transmitting with the body coil and using large RF deposition sequences.

The equation for *SAR* is:

SAR is proportional to $B_0^2 \, \alpha^2 \, D$,

where B = static magnetic field, α = flip angle and D = duty cycle.

The duty cycle relates to the number of RF pulses per TR period and includes fat suppression, magnetization transfer, presaturation pulses and ETL.

As many paediatric patients are sedated, physiological changes may affect image quality, especially in the brain. For example, the PCO_2 may become elevated (this is more pronounced in anaesthesia with or without volatile anaesthetic agents where respiratory support is not provided) leading to several noticeable changes in image contrast and quality. First, even a small increase in PCO_2 accentuates pulsatile artefacts from large CSF-filled structures, especially around the third ventricle. Secondly, an increase in PCO_2 causes small intracranial vessels to dilate, which can potentially improve the quality of intracranial MRA. This phenomenon

15

permits the use of larger flip angles and shorter TRs to produce angiograms with good SNR and improved conspicuity of smaller peripheral vessels. Newer image reconstruction techniques, such as parallel imaging, may not be as effective in the paediatric environment due to the anticipated reduction in SNR. Small FOV and higher through-plane resolution may preclude the use of parallel imaging.

Smaller coils can often be used, thereby increasing local SNR. For example, a small child's body can be examined in the head coil rather than the body coil. Surface coils often give sufficient signal coverage and depth to scan large areas. If examining the torso, it is wise to raise the child and coil using pads so that the area under examination is nearer to isocentre. This not only improves SNR but also enables the implementation of a rectangular/asymmetric FOV for imaging the spine, chest, abdomen, and pelvis. However, with more flexible off-centre capabilities and rectangular/asymmetric FOV options, this strategy may not be necessary. Contrast characteristics in children are similar to those in adults and therefore parameters such as TR, TE and flip angle are comparable. The main exception to this is in the neonatal brain, where myelination patterns and increased water content necessitate the use of a much higher TR in CSE sequences than adults (see *Brain,* below).

It is essential that a sedated patient be as comfortable as possible during the examination and care should be taken to ensure that adequate padding is used around pressure points. This is particularly important in cases of myelomeningocele and sacrococcygeal teratoma. A sedated patient can quickly lose body heat so it is essential to provide adequate thermal support. A small baby can lose up to 50% of its total body heat from the head so take particular care in adequately covering this. In providing blankets or other coverings to maintain temperature, remember to use material that is static resistant. Ear protection is still a vital component of patient care and, due to the variable size of children, the range of hearing protection material used may need to be revised. A combination of mouldable disposable ear plugs and normal headphones usually suffices.

Common indications for paediatric imaging are:

Brain

- Congenital developmental anomalies (Chiari, heterotopia, cortical malformations, neuronal migration).
- Metabolic (Leigh's disease, Wilson's disease, lipid storage diseases).
- White-matter diseases (dysmyelination, demyelination).
- Hydrocephalus.
- Tumours.
- Neurofibromatosis, tuberous sclerosis.
- Epilepsy (mesial temporal sclerosis).
- Infective processes (abscess).
- Destructive processes (encephalomalacia).
- Trauma.

MRA

- Congenital vascular anomalies.
- AVM – pre- and post-embolization.
- Infarct/ stroke.
- Vasculopathy.
- Pre-surgical tumour resection.
- Venous thrombosis.

Spine

- Congenital lesions (Chiari, myelomeningocele, lipoma, tethering, diastematomyelia).
- Scoliosis.
- Canal stenosis typically achondroplasia.
- Tumours (intramedullary, extramedullary).
- Trauma.
- Infective (discitis, osteomyelitis).
- Inflammatory (transverse myelitis, Guillain-Barré).
- Degenerative (disc disease, spondylolisthesis).
- Syringomyelia, hydromyelia.
- Brachial plexus, obstetric injury.

Musculoskeletal

- Congenital cartilage anomalies such as discoid meniscus.
- Trauma, sporting injuries.
- Avascular necrosis/osteochondritis dissecans.
- Growth plate anomalies.
- Intra-articular foreign bodies.
- Tumours (osteosarcoma, Ewing's sarcoma, rhabdomyosarcoma).
- Evaluation of congenital dislocation of the hips.
- Lymphatic or vascular malformations.

Body and cardiac

- Diagnosis of undescended testicle.
- Congenital abnormalities of the reproductive system.
- Imperforate anus, developmental pelvic anomalies (bladder exstrophy).
- Evaluation of congenital cardiac and great vessel anomalies.
- Tumours (Wilms', hepatoblastoma, cardiac).
- Liver (including MRCP) and renal (including MRU and functional studies).
- Vascular abnormalities.
- Liver and cardiac iron studies.

15

Brain imaging

Imaging protocols must make provision for imaging the immature and mature paediatric brain. As the brain matures there are quite noticeable changes in contrast on both T1 and T2 weighted images, as compared with that of the mature brain. These changes reflect the relative concentrations of free water and compounds responsible for myelination. In most texts the brain is considered mature by 18–20 months. Before this T1 and T2 weighted images play differing roles in the assessment of brain maturation. In the first few months of life, T1 weighted images are important to determine normal myelination, whereas later T2 weighted images are more sensitive. Prior to full maturation it is necessary to use longer TRs and TEs to obtain good T2 weighting. The increase in TE will also necessitate a corresponding change in TI and TR in FLAIR FSE sequences.

Brain protocols in the adult population have been comprehensively discussed earlier in this book but paediatric considerations are outlined below. It is impossible to use a single imaging protocol to address the plethora of paediatric clinical presentations. All the suggestions given below depend upon your system's hardware and software (prospective and retrospective reconstruction capabilities) and the individual preferences of your reporting and referring clinicians. In general, however, the protocols listed should cover most eventualities.

Axial/coronal FSE T2 (Figures 15.1 and 15.2)

It is imperative that imaging of the developing brain is not restricted to a single imaging plane. Recent advances in time efficient 3D T2 sequences offer the ability to obtain high in-plane resolution with isotropic voxels in under 6 minutes. In most institutions FSE techniques are considered the optimal sequences, obtaining good quality T2 weighted images in a short scan time. Long ETLs and TRs combined with fine matrices are required. Recent advantages in RF and gradient technology have enabled more flexible combinations of long ETLs and echo spacing, which if used appropriately can have dramatic effects on the ability to visualize tissues with a short T2 and small lesions (see *Pulse sequences* in Part 1). In cases of suspected demyelination or acute disseminating encephalomyelitis (ADEM) it is essential to perform a T2 weighted sequence to evaluate the corpus callosum.

FLAIR FSE (Figures 15.3 and 15.4)

The advent and further refinement of these sequences has greatly enhanced the conspicuity of many intracranial lesions. In some pathological processes such as neurofibromatosis, tuberous sclerosis and medul-loblastoma the addition of water excitation or fat suppression to the FLAIR sequence has greatly increased its diagnostic sensitivity negating the use of proton density or balanced images. The diagnostic sensitivity of FLAIR may also be improved with high resolution isotropic 3D data sets.

15

Figure 15.1 Axial FSE T2 weighted image in a 4-month-old child. Polymicrogyria and gliosis are clearly seen and may represent an hypoxic incident.
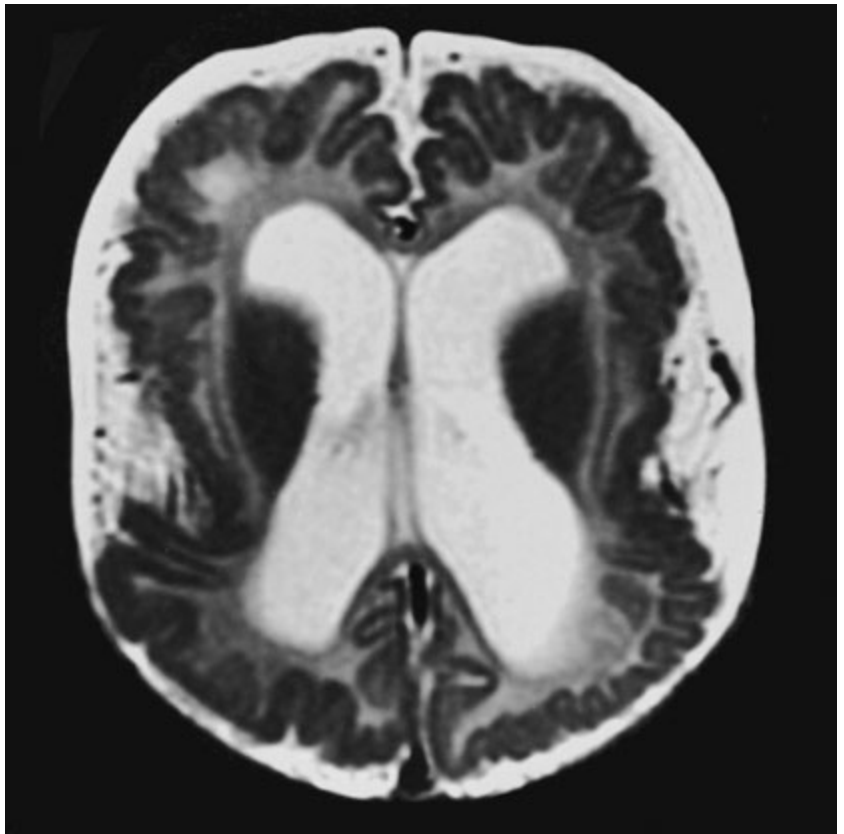
Figure 15.2 Coronal FSE T2 weighted image demonstrating a double cortex in a child with developmental delay.
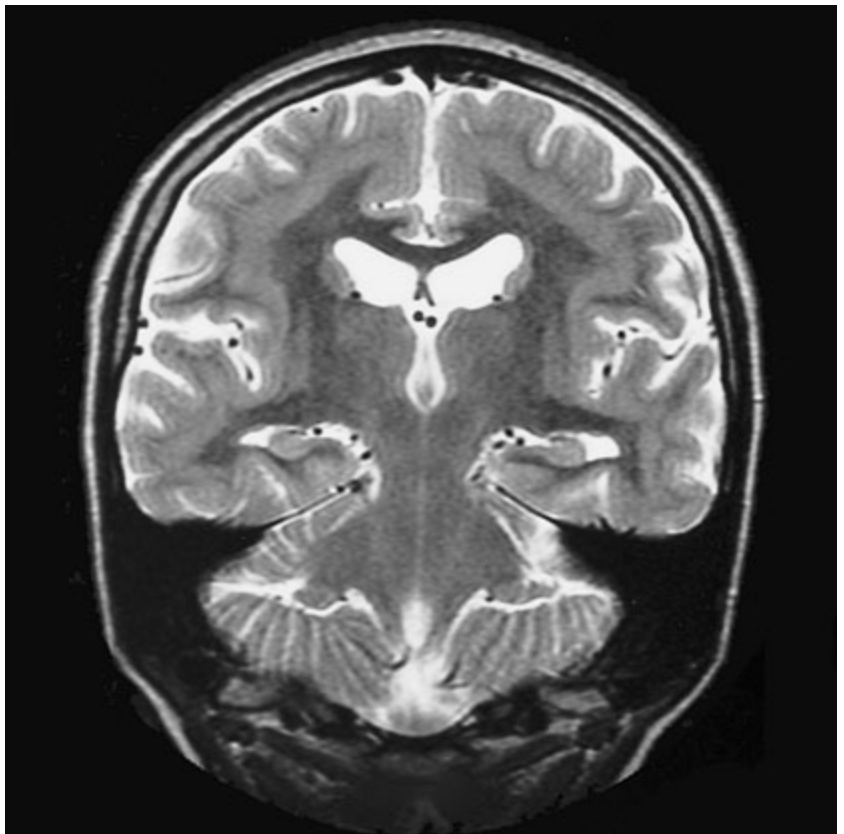
Figure 15.3 Axial FLAIR susceptibility weighted image of the brain demonstrating metastases from a highly malignant sarcoma.

15
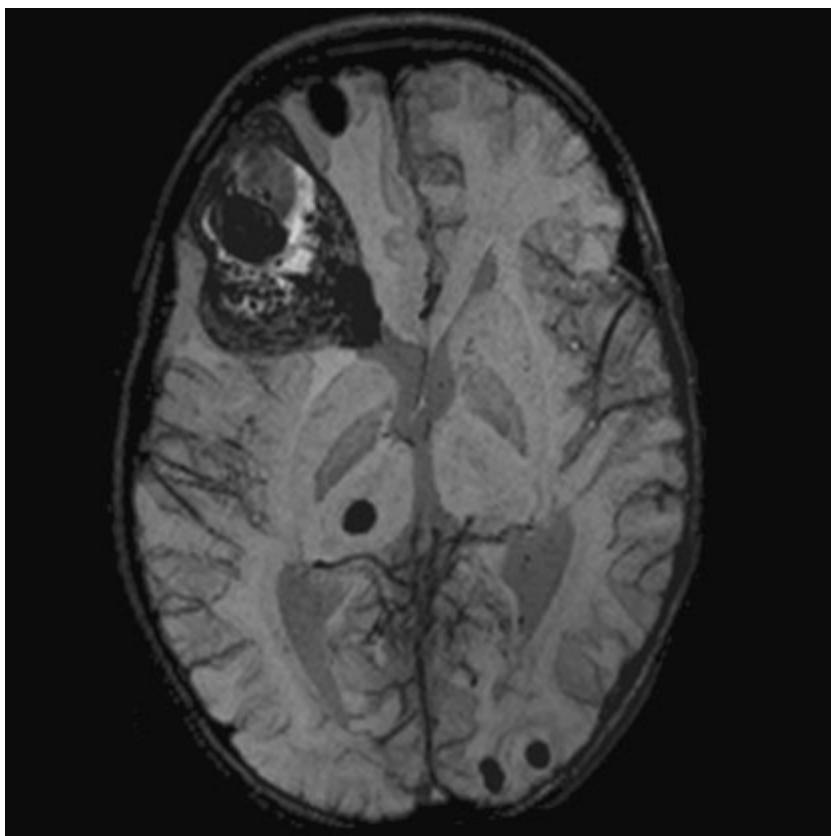
Figure 15.4 Axial 3D water excitation FLAIR image of the same patient in Figure 15.3.
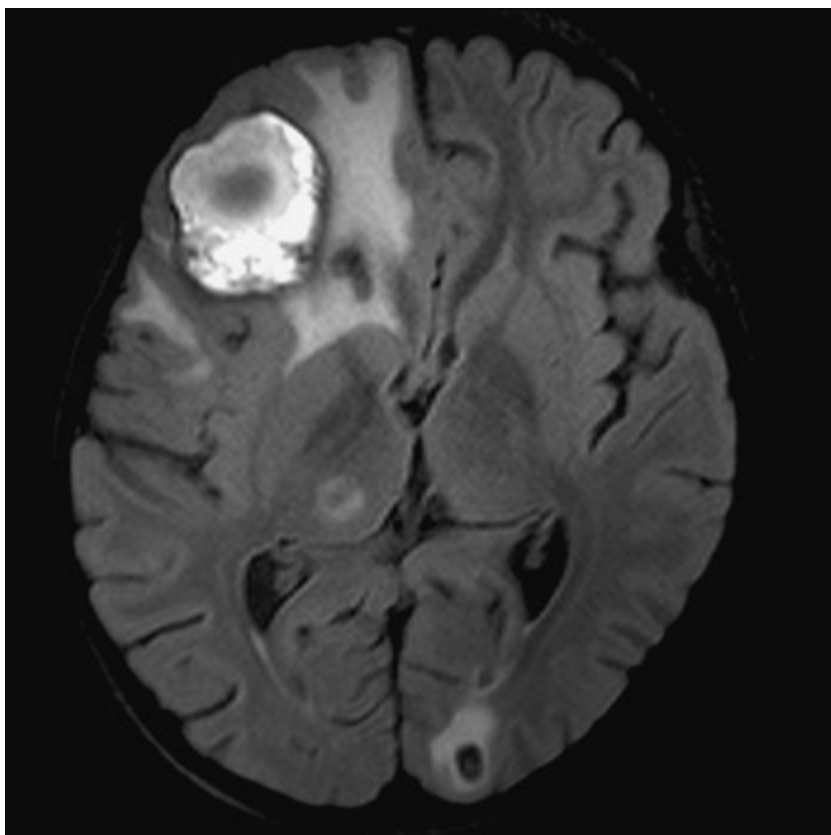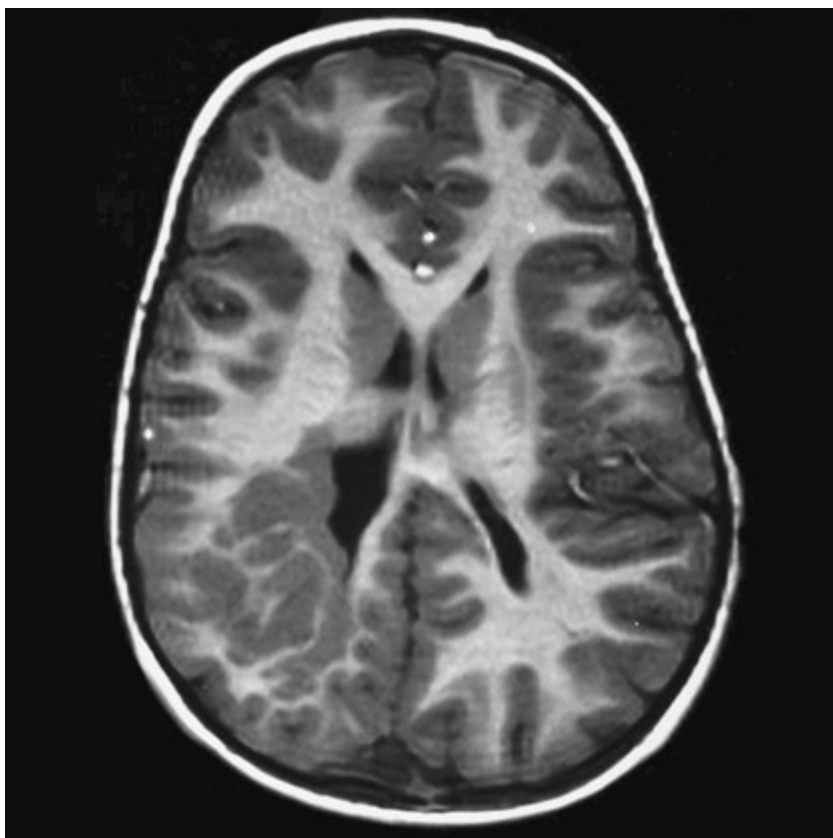
Figure 15.5 3D incoherent (spoiled) GRE reformatted in the axial plane demonstrating transmantle dysplasia.

2D/3D FSE/incoherent (spoiled) GRE +/− IR T1 (Figure 15.5)

The choice of sequence for T1 weighted imaging depends on the required field strength, resolution and image contrast. One option is to use 3D fast GRE with an inversion pulse (e.g. MP RAGE) as it provides a balance between image contrast, spatial resolution, flexibility, durability and scan time. If 2D imaging is preferred, it is essential to obtain sagittal images for posterior fossa pathologies. Otherwise either axial and/or coronal imaging is usually preferable. Historically, T1 weighted SE sequences have been conventionally utilized but with refinements in FSE, such as shorter echo spacing and higher receive bandwidths, this sequence is now considered a more time-efficient alternative.

Post-contrast imaging should be obtained in a minimum of two planes and one of these may include the use of MT. The literature contains many references relating to improved lesion conspicuity using MT. The detection of subtle, small pathologies such as metastases and meningeal disease are enhanced using MT. Some normal anatomical structures can exhibit hyperintensity on MT sequences, therefore it is often wise to obtain a pre-contrast MT as well as a post-contrast series. The addition of a MT to the sequence reduces the amount of slices available per TR, and it may be

15

preferable to obtain images in two acquisitions using a short TR, than increase the TR (and hence reduce T1 weighting) to obtain coverage. Some centres prefer to use a 3D sequence post-contrast acquisition. This sequence should preferably employ water suppression techniques, thin slice isotropic voxels and, depending upon the imaging coil, parallel imaging techniques.

To evaluate the immature brain it is important that the 3D sequence allows the flexibility to vary the TI or magnetization-prepared time to visualize physiological changes within the brain. This requirement to modify the inversion time is more critical in sequences that employ centric filling of k-space. As the brain matures, shorter TIs are required. Although the appropriate values will depend on field strength, a TI range from 900 ms for newborn infants to 350 ms for matured brains is common. This strategy permits visualization of myelination processes and developmental anomalies, even through the transition period when grey and white matter have similar signal characteristics on T2. Some sites elect to use a single or dual inversion STIR sequence for this purpose.

Susceptibility weighted imaging/GRE/SE-EPI sequences
(Figures 15.6 and 15.7)

These sequences play an important role in trauma, metabolic disorders and perinatal infections where the visualization of haemorrhage/calcium is required. With the advent of sequences using multiple 180° RF pulses, the ability to detect calcium/haemorrhage is somewhat compromised at low and mid-field (0.35–1.5 T) so it is necessary to include a sequence that emphasizes these appearances in clinically suspected cases. Historically, this has been achieved using a conventional GRE sequence but it is possible to obtain higher resolution and faster scans by using purposely designed susceptibility weighted sequences (SWI) or multi-shot EPI sequences (GRE or SE).

Diffusion

DWI sequences now play an integral role in diagnostic protocols. They are commonly performed in cases of suspected infarction, asphyxia, trauma (looking for the sequelae to petechial haemorrhage), cysts (cyst vs. epidermoid) and intracranial tumours (see *Pulse sequences* in Part 1 and *Brain* under *Head and neck* in Part 2). Diffusion tensor imaging (DTI) or tractography sequences are proving useful in cases of congenital/cortical malformations, tumours and infarction. It has been postulated that DTI may have a pivotal role in the evaluation of tumour seeding along white matter tracts in invasive tumours such as glioblastoma multiforme. DWI and DTI offer a quantitative approach to the evaluation of lesions involving the brain, spinal cord and abdominal organs by using apparent diffusion coefficients, fractional and regional anisotropy. Parallel imaging is routinely used in DWI/DTI especially at higher fields to reduce the geometric distortions caused by magnetic susceptibility.

15

Figure 15.6 Coronal T2 FSE (left) and GRE-EPI (right) showing subtle early calcification (arrow). Note how well this abnormality is seen on the GRE-EPI image compared to the FSE, due to susceptibility effects.
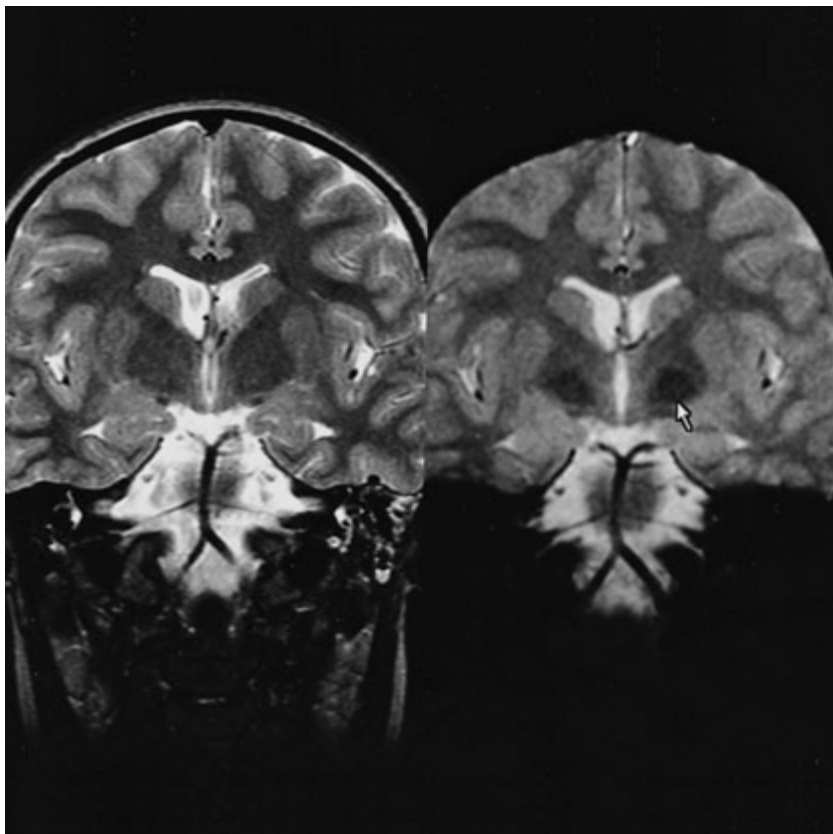
Figure 15.7 Axial SE-EPI demonstrating chronic haemorrhage.

15
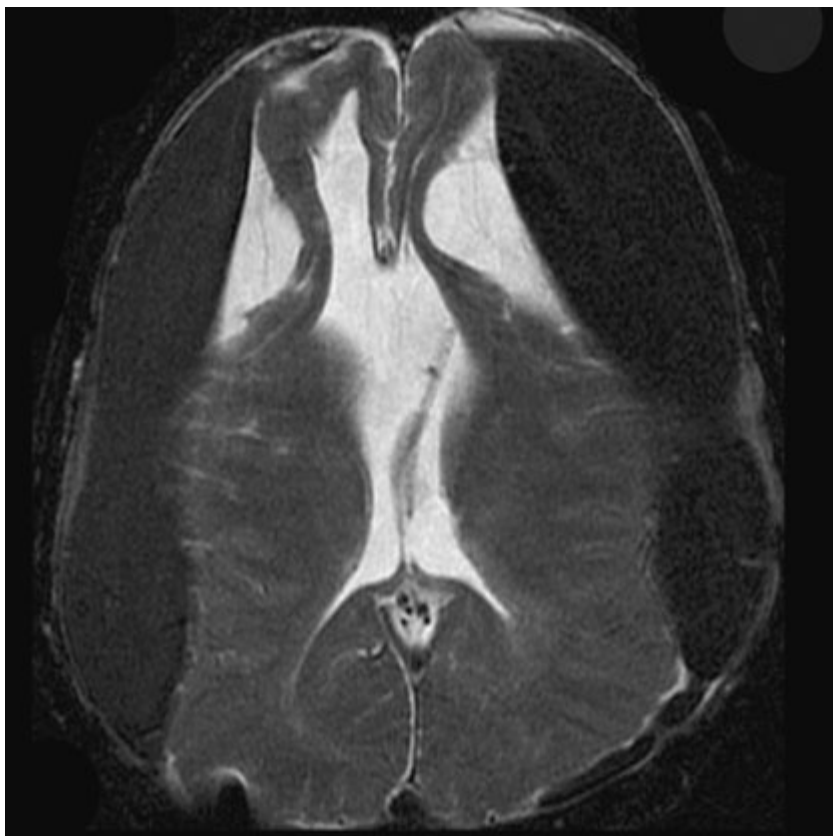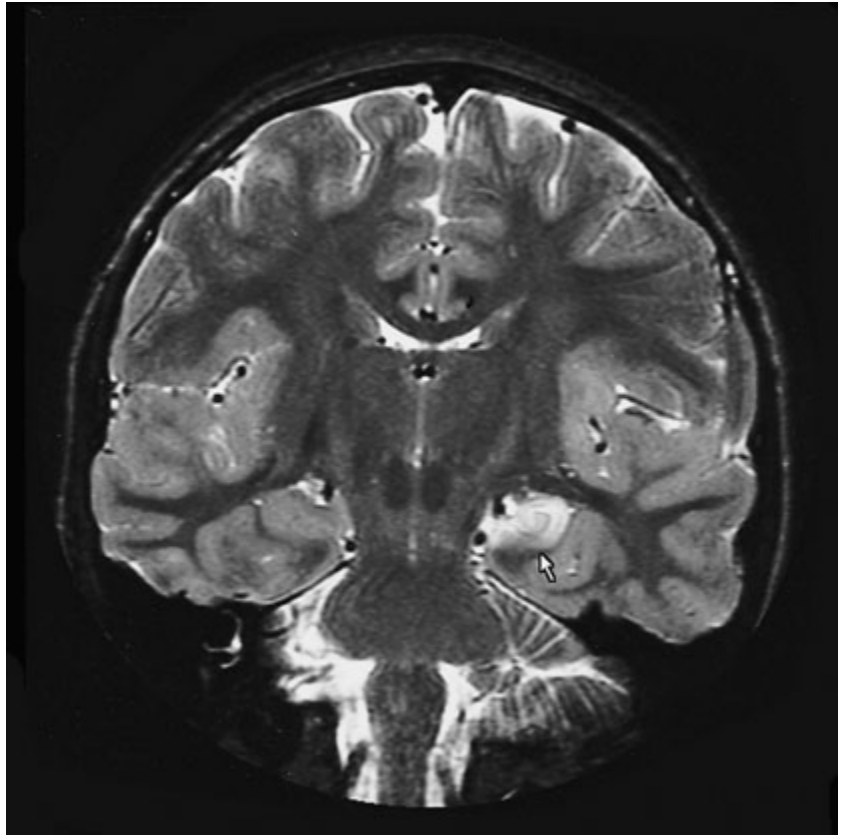
Figure 15.8 Coronal FSE T2 weighted image demonstrating mesial temporal sclerosis (arrow). This is a common cause of epilepsy.

Epilepsy (Figure 15.8)

Temporal lobe epilepsy (TLE) (complex partial seizures) is probably one of the most common requests for paediatric brain imaging, and the complete evaluation of these patients can be time-consuming. In addition to evaluating the temporal lobes, a standard brain protocol must also be performed as approximately 30% of lesions presenting as TLE are outside the temporal lobes. FLAIR FSE (rather than EPI sequences), in either the coronal or sagittal planes, is necessary to evaluate the hippocampus. EPI sequences produce susceptibility from the petrous bones and, as thin slices are required to achieve adequate resolution in this area, SNR is compromised.

To evaluate the temporal lobe and hippocampus completely, the examination must include sequences that detect signal changes within the hippocampus, atrophy and the internal architecture of the hippocampus. The slice plane should be orientated perpendicular to the line of the hippocampus. IR–FSE, with a medium TI, a short ETL and fine matrices, is a useful sequence to visualize the internal architecture of the hippocampus. Many sites attempt to gain these types of images using longer ETLs but blurring often compromises some of the spatial resolution. Isotropic 3D sequences

are extremely valuable assets when evaluating epilepsy as the images may be reformatted into other orthogonal and oblique orientations. In addition, volumetric measurements of the hippocampus and rendered or curved reformats of specific anatomical regions are possible. These sequences should be reformatted in a minimum of two planes. The choice of sequence for the volume is usually an incoherent (spoiled) GRE with or without some type of preparation pulse, but some sites are experimenting with 3D FSE for volumetric studies. Pre-Fourier manipulation techniques allow high-resolution, short TE images to be obtained in shorter scan times, and further development and refinement of these sequences should lead to their increased use in the future. Finally, patients that present with seizures must have an examination that includes high-resolution sequences (sagittal and coronal) of the hypothalamic region.

Pituitary disease (Figure 15.9)

The main indications for imaging the pituitary/optic chiasm in paediatrics are failure of the pituitary gland to develop normally (e.g. ectopic posterior pituitary), hamartomas, tumours (craniopharyngiomas, astrocytomas, gliomas) and neurofibromatosis. In children under 8 months the most
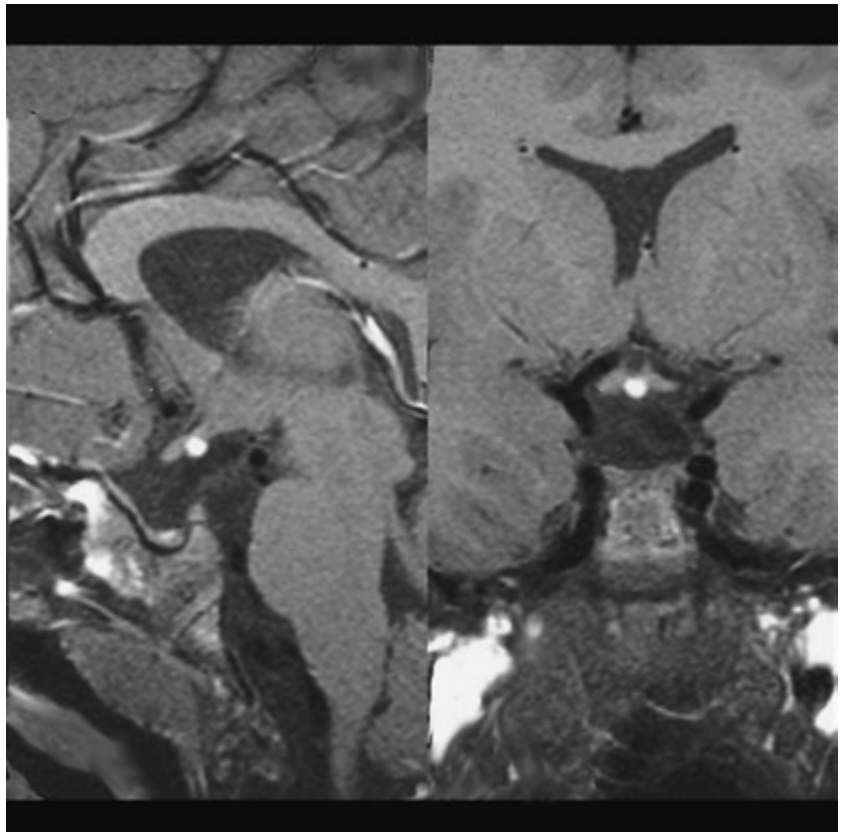
Figure 15.9 Sagittal (left) and coronal (right) T1 weighted images after contrast showing an ectopic posterior pituitary.

15

common intracranial tumours are astrocytomas arising from the optic chiasm. Investigation of developmental anomalies must include T1 weighted images in the sagittal and coronal planes. The choice of sequence depends upon the quality of the head coil and range of sequences available. Ideally, images are obtained with a small FOV and thin contiguous slices (minimum slice thickness 2.5 mm). In SE it is necessary to use multiple NEX/NSA and a narrow receive bandwidth to obtain sufficient SNR. These sequences are, therefore, time-consuming and an incoherent (spoiled) GRE volume sequence using an isotropic dataset ($0.8 \times 0.8 \times 0.8$ mm) may be preferential. The advent of more time efficient 3D T2 weighted sequences such as SPACE have enabled the inclusion of thin slice isotropic T2 sequences to be added to the protocol. If a hyperintense signal is seen in the region of the pituitary stalk, tubercinerium and hypothalamus, an additional chemical/spectral presaturation sequence, post-contrast, is necessary.

Tumours (Figure 15.10)

It is important to include protocols for metastatic and non-metastatic lesions and supratentorial and infratentorial lesions. All potential metastatic lesions must include pre-operative post-contrast imaging of the spine
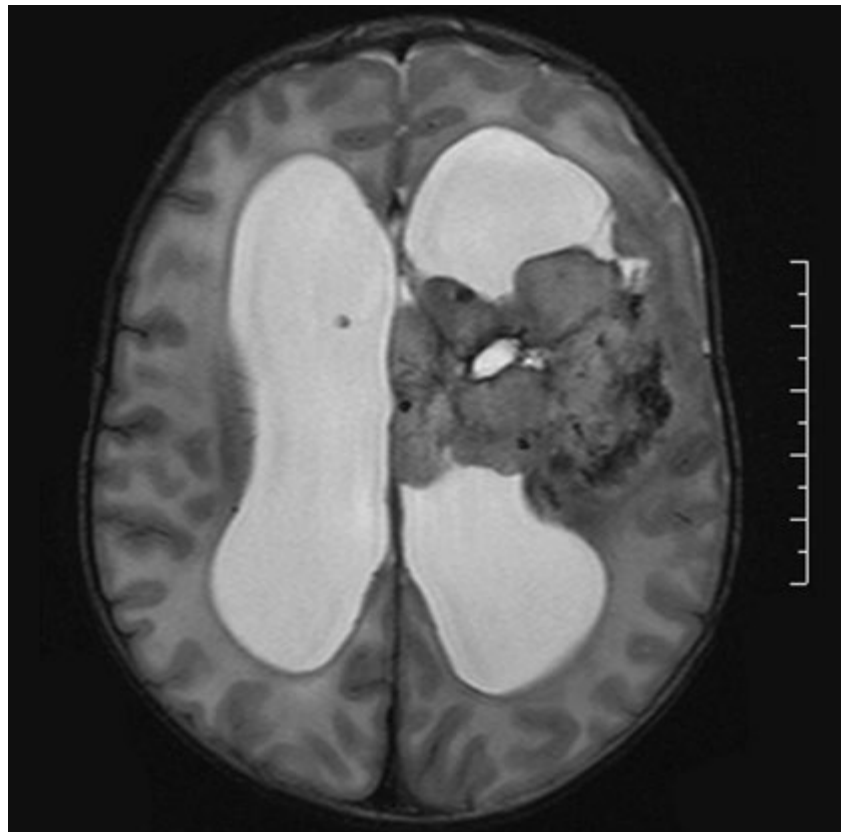
Figure 15.10 Axial FSE T2 weighted imaging demonstrating a neonatal glioblastoma.

15

looking for drop metastases. The necessity for pre-operative spinal imaging can present problems, especially with the sedated patient, but assists neuro-oncologists in determining the grade of tumour for treatment. An important component of tumour protocols is the maintenance of consistent scan plane orientation, slice thickness, interslice spacing and FOV, which makes comparisons between pre- and post-therapy scans easier. Basic protocols should include T2 weighted images, FLAIR or proton density, some form of pre- and post-contrast T1 weighted imaging and a GRE sequence looking for haemorrhage or calcium.

One of the problems of scanning patients with posterior fossa lesions is the effect of contrast on the venous sinuses and increased pulsatility artefacts. There are several ways to reduce these effects including using a shorter TE, 3D GRE, GMN and gated studies. Post-operative examination timing has been a controversial point and the policy of your unit will ultimately reflect the treating physician's preferences. The main disadvantages of scanning patients within this post-operative window are pain from lying on the incision, vomiting, headache and general lack of cooperation. However, careful patient preparation, including mild sedation, antiemetics and pain relief, often minimizes these effects. If the tumour compromises vascular territories a diffusion sequence can be an advantage. MRA is often helpful in cases of hypothalamic and large pituitary-based lesions to assist in surgical planning. MR venography should be routinely performed in cases where lesions are adjacent to venous structures, especially the tentorium.

Hydrocephalus

MRI plays a very important role in the evaluation of the anatomical regions adjacent to the third and fourth ventricle in cases of suspected obstructive hydrocephalus. The majority of these lesions are due to seemingly benign lesions such as hamartomas or anatomical variants of the aqueduct, e.g. aqueductal web. The initial examination should include the whole brain using axial dual echo FSE with thin slices and sagittal T1 and T2 weighted images. As hamartomas tend to have a higher conspicuity on PD weighted images, a FSE sequence is preferable to FLAIR. High-resolution images utilizing thin slices in the sagittal plane demonstrate obstruction of the aqueduct, flow voids and anatomy. Benign hamartomas can develop an aggressive phase, therefore contrast should always be given, despite the low diagnostic yield. 2D cine PC-MRA can be important to quantitatively and qualitatively measure CSF flow through the lesion. This is not essential in static lesions but is crucial in the evaluation of aqueduct webs or partially obstructive adhesions.

MRA (Figures 15.11 and 15.12)

MRA examinations on children generally obtain greater small vessel conspicuity than in adults due to the lack of peripheral vascular disease and the physiological changes due to sedation. These properties inherently

15
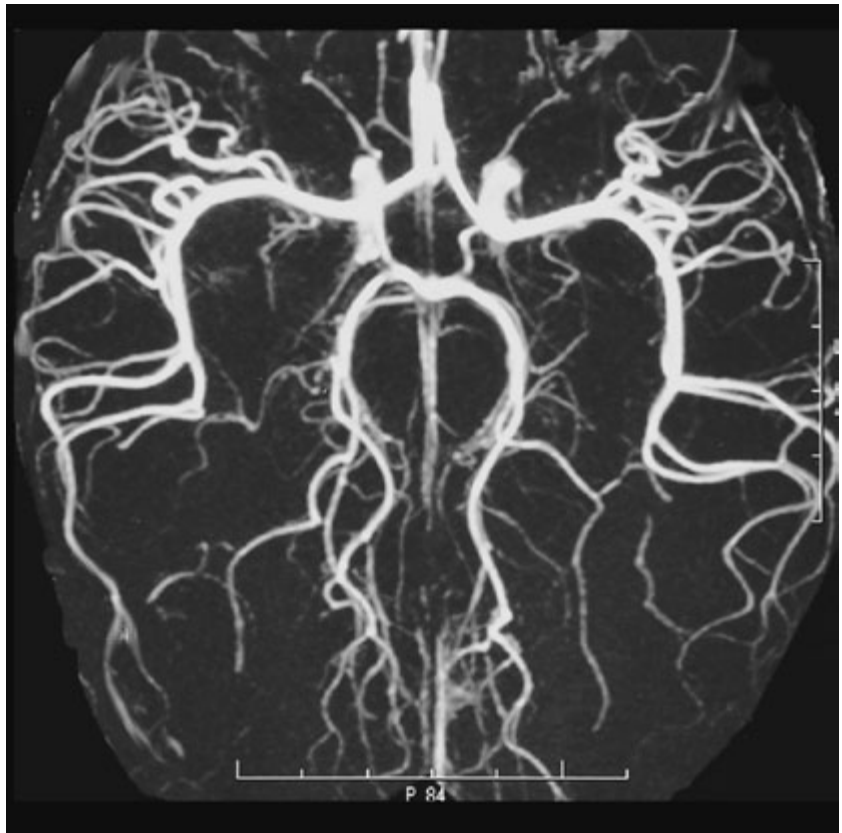
Figure 15.11 3D TOF-MRA in a 4-year-old child showing normal appearances.
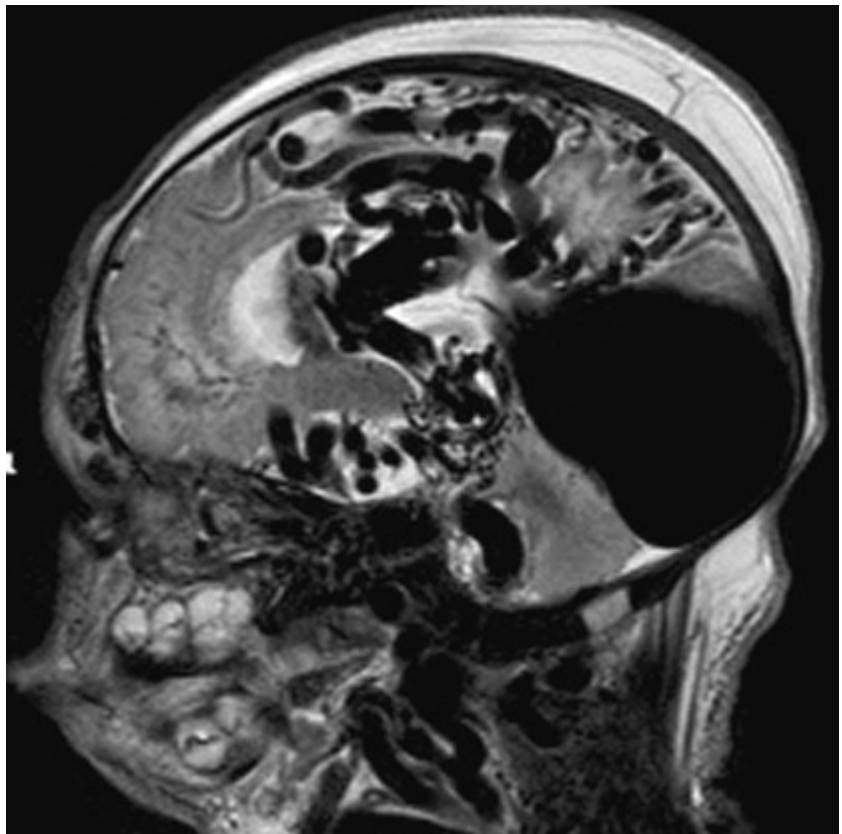
Figure 15.12 Sagittal image showing a Vein of Galen malformation.

15

allow a larger flip angle (5–10% larger than in adults) and a reduced TR. The inflexibility of partition numbers may cause problems regarding the appropriate TR to use for a given imaging volume. The use of a ratio of TR divided by each imaging volume of 0.7 (0.6 for sedated patients) often obtains a balance between scan time, vessel conspicuity and patient acceptance. One of the most common errors in prescribing the imaging volume per TR is to make the volume too large, requiring a longer TR to reduce saturation effects. A maximum volume of 64 mm per acquisition in single- or multiple-slab sequences is usually optimal. Multiple-slab sequences are performed where large anatomical coverage is required. The scans are obtained by acquiring the most superior slab first. Ramped RF and MT are routinely used for 3D TOF sequences. The hyperintense appearance of fat should not present a diagnostic problem as this can be removed by careful manual segmentation during post-processing. Where possible, MRA sequences should utilize image interpolation to increase spatial resolution and reduce TEs with minimal SNR trade-offs. Contrast is rarely indicated in TOF sequences with the exception of small babies less than 2 weeks old. Using a small dose of contrast often greatly enhances the diagnostic yield in these children.

Although TOF techniques are the most commonly used sequences, there are clinical indications for performing PC-MRA. 2D PC-MRA techniques are useful in examining the sagittal sinus and to screen AVM patients prior to a more complex TOF sequence. Current developments using segmented K space will improve the performance and spatial resolution of this sequence, and fast 3D PC-MRA techniques will increase its clinical acceptance. Contrast-enhanced MRA is now an important tool in the evaluation of complex AVMs. The best clinical results are obtained using magnetization-prepared 3D fast GRE sequences using interpolation techniques pre- and post-contrast. A post-processed image is obtained using data subtracted from the pre- and post-contrast sequences.

Extracranial lesions, such as carotid disease and AVMs, can be visualized using 2D TOF sequences but suffer from long scan times. Significant improvements in system capabilities now provide gated fast-segmented K space GRE sequences and, therefore, contrast-enhanced 3D GRE may be a preferred option, especially when examining extracranial carotids.

Spine imaging (Figures 15.13–15.20)

The criteria used for sequence and protocol selection are similar to the adult population (see section on the *Spine*) with a few modifications. In all spinal imaging, slice prescription must accommodate the smaller transverse diameter of the cord and, as such, the maximum slice thickness should be 3.5 mm in the sagittal and coronal planes and 4 mm in the axial plane. Examinations for congenital lesions must obtain images of the whole spine as there can be a related pathology (tethering, Chiari, syrinx) at a different level. These scans must include sequences to evaluate anatomy and pathology in two planes. In cases of lipoma, sinus tract or tethering it

15

Figure 15.13 Sagittal (left) and coronal (right) FSE T1 weighted images through the thoracolumbar spine demonstrating diastematomyelia (arrow), a tethered cord and an intramedullary cyst.

15

Figure 15.14 Sagittal FSE T2 weighted image showing a cyst (arrow) that, in this case, mimics the conus and obscures a tethered cord.

Figure 15.15 Sagittal T1 (left) and T2 with chemical presaturation (right) clearly demonstrate an intraspinal lipoma.

Figure 15.16 Sagittal T1 weighted images post-contrast of the cervical and thoracic spine (left) and the lumbar spine (right). Areas of enhancement represent seeding from a medulloblastoma. Note the markers placed on the back for localization.

15

Figure 15.17 Sagittal FSE T2 weighted image of the cervical spine showing an intramedullary astrocytoma.

15

Figure 15.18 Sagittal FSE T2 weighted image with chemical presaturation demonstrating discitis and osteomyelitis of L5/S1.
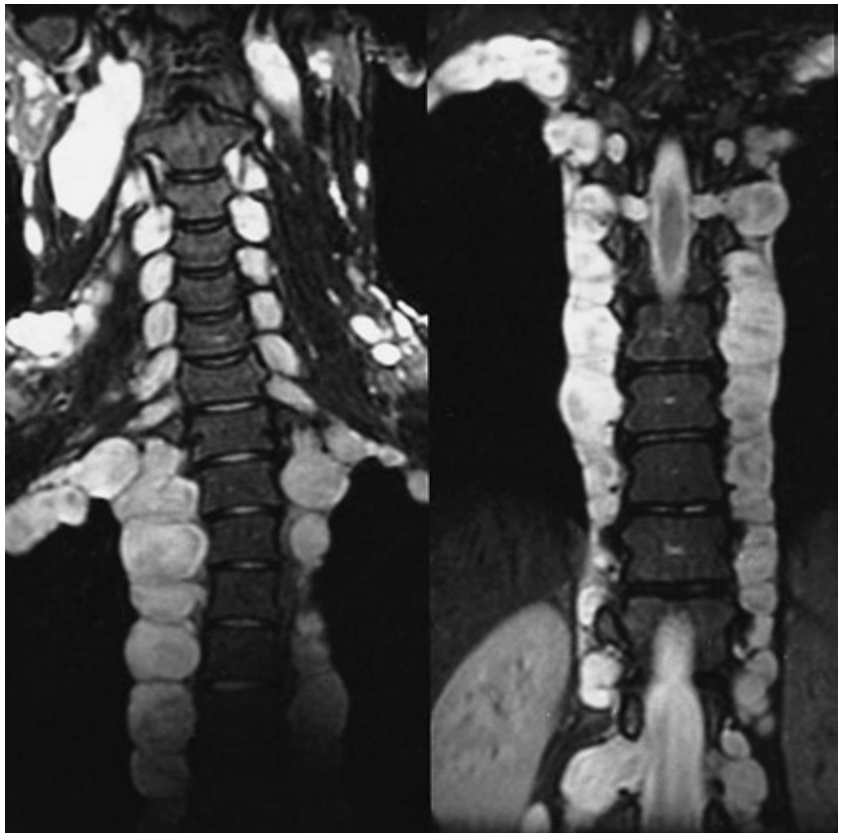
Figure 15.19 Coronal FSE T2 weighted images. Neurofibromatosis lesions are clearly seen.

Figure 15.20 Sagittal FSE T2 weighted image showing a large teratoma.

15

is important to include a sagittal series (preferably T2) using chemical/ spectral presaturation techniques. MRI markers should be placed near sinuses, haemangiomas or defects to localize an extension into extra-medullary spaces. The study of patients for tethering or retethering should include a sequence to demonstrate cord mobility such as scanning the patient prone and supine, PC cine analysis of motion or RF tagging. Initial studies for tumours pre-biopsy must include post-contrast imaging of the whole spine looking for distant metastases. Always include a wide FOV localizer (C2 downwards) or another localization method to enable identification of correct vertebral levels.

Scoliosis

Scoliosis is the abnormal curvature of the spine which is most apparent in the coronal plane. This abnormal curvature of the spine is associated with a degree of axial rotation of the vertebral bodies and there may also be an accompanying curvature in the sagittal plane either lordosis or kyphosis.

Scoliosis is a relatively common spinal abnormality in adolescence and may be associated with pain and, depending upon the degree of spinal curvature, severe physical disability.

Scoliosis may be classified as:

- Congenital – which is caused by vertebral anomalies of embryonic origin. These cases usually present in early childhood.
- Degenerative.
- Neuromuscular.
- Idiopathic – this type of scoliosis can be further subdivided, based upon the age of presentation into infantile, juvenile and adolescent.

Not all patients presenting with scoliosis require MR imaging but those who present with atypical signs consistent with changes in the features of the curve such as rapid progression of the curve, an abnormal location of the curve apex, pain, neurologic dysfunction or other associated anomal-ies such as VATER syndrome, Marfan's or neurofibromatosis are often referred for an MR examination.

The role of MR imaging is to characterize any associated anomaly of the neuroaxis, monitor the appearances of associated pathologies such as syrinx or cord tumour and to identify any occult pathologies that may coexist with the scoliosis. The examination must include imaging from the most superior margin of the pons to the base of the spine. It is imperat-ive to perform a protocol that identifies any adjunct pathology (e.g. spinal cord tumour, syrinx, tethered cord or Chiari malformation) as well as providing surgeons with information crucial to reconstructive surgery. The actual protocol chosen will reflect the individual preferences of the reporting radiologists but a minimum protocol is outlined below.

- *Sagittal FSE/SE T2* of the cranio-spinal junction to determine the position of the cerebellar tonsils. The minimum slice thickness should be 3 mm and must have coverage from pedicle to pedicle.
- *Sagittal FSE/SE T2* to identify the position of the conus.

- *Coronal FSE/SE T2* using a wide FOV to identify the course of the cord and its relationship to the curve associated with the scoliosis.
- *Axial SE/FSE/T2* from the superior margin of the pons to the most distal portion of the cord. Slices must be aligned parallel to the line of the vertebral bodies and the angle of the curve. The FOV should be large enough to identify neural tumours such as neurofibromatosis.
- *Axial SE/FSE T1* may be included targeted at the level of the curve to determine pedicle measurements. In the case of an associated syrinx post contrast imaging should be included to rule out an associated tumour.

New techniques available on some systems have aided the evaluation of scoliosis patients. 3D sequences have assisted the evaluation of scoliosis examinations by acquiring isotropic voxels capable of multi-planar reformations that enable a more thorough evaluation of complex curves. The ability to stitch or compose coronal images gives surgeons a more structured view of the complexity of the curve.

Musculoskeletal imaging (Figures 15.21–15.24)

MRI in paediatric musculoskeletal imaging has always played an integral part in patient treatment. Paediatric musculoskeletal imaging is similar to that of adults for the evaluation of sporting injuries, avascular necrosis, painful joint evaluation and soft tissue or bone tumours. Paediatrics also involves the evaluation of congenital lesion such as achondroplasia, growth plate injuries and complete evaluation of articular cartilage.

Generally, the ROI is smaller and images with a much higher in-plane and through-plane spatial resolution are therefore required. The quality of current array and quadrature coils and higher field strengths enables the use of small FOVs, thin slices, chemical/spectral presaturation GRE and FSE/SE sequences. Wide bore designs and relatively homogeneous magnets enable children to be scanned in all anatomical positions. This ease of positioning can create problems with chemical/spectral presaturation techniques leading to variations in the quality of suppression. It is sometimes necessary to use filler bags to create a more uniform anatomical region, and higher order manual shims to improve the local homogeneity. When examining small areas such as the patella, talus, wrist and elbow, use a small FOV in conjunction with single or array coils. In joint imaging always use the smallest possible coil to cover the suspected pathology. However, as a caveat, smaller coils are sometimes more difficult to position and immobilize and if the coil is uncomfortable any potential resolution and SNR gains may be lost by patient movement.

The evaluation of avascular necrosis and osteochondritis lesions requires information about the exact anatomical location of the lesion, presence of free fluid, state of articular cartilage, intra-articular foreign bodies and extent of associated bone contusion. The aim is to provide enough diagnostic information about the status of the articular cartilage and potential free

15

Figure 15.21 Coronal T1 weighted image through the ankle joint showing a Brodie's abscess.

15

Figure 15.22 Coronal FSE T1 (top) and coherent GRE with chemical presaturation (bottom) demonstrating a growth plate bar of the humeral head following osteomyelitis.
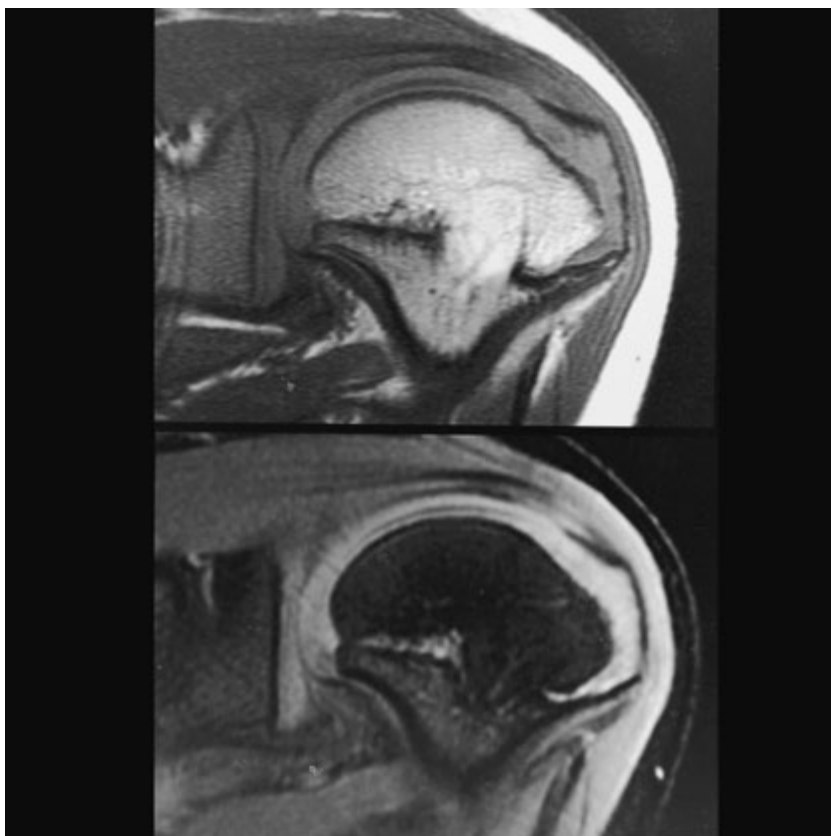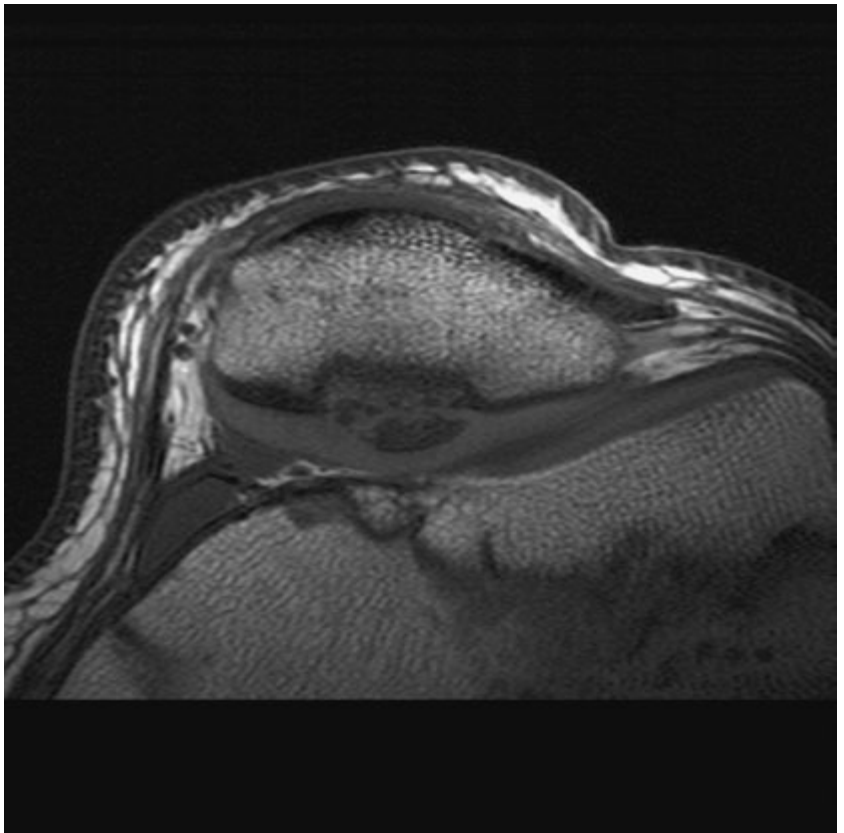
Figure 15.23 Axial image showing osteochondritis dissecans.

Figure 15.24 Coronal image of the spine showing Ewing's sarcoma.

15

bone without the necessity for intra-articular contrast. When results are ambiguous it will be necessary to introduce gadolinium into the joint. The least invasive option is via an indirect route followed by exercising the joint and re-scanning. This technique will suffice in approximately 75% of cases, but if it is necessary to resort to a direct joint injection some form of sedation will be necessary. Re-scanning with higher spatial resolution, more optimal surface coils and more appropriate sequences may, however, suffice.

Growth plate evaluation is often requested after trauma and before surgery. This is best achieved using chemical/spectral presaturation 3D GRE imaging with isotropic voxels allowing for reformations in the sagittal and coronal planes. The addition of PD or balanced high resolution coronal and sagittal images also assist in the evaluation of the growth plate. With current coil design thin slices with no gap are achievable whilst maintaining adequate SNR. Tl weighted sequences are of less value in this condition due to potential chemical shift artefact obscuring the growth plate.

Tumour protocols should be designed for either soft tissue lesions such as rhabdomyosarcoma or bony pathology such as osteosarcoma or Ewing's sarcoma. They should always be performed pre-biopsy. Bone tumour protocols must provide the following information:

- Intraosseous cortical and medullary component including skip metastases. This is accomplished by performing oblique coronal imaging along the entire long bone joint to joint. If the coil does not cover the entire limb move it and repeat the sequence or use the body coil. The contralateral long bone should also be examined for comparison in the visualization of marrow changes and skip metastases.
- Soft tissue component, relationship to muscle planes and neurovascular bundle. Axial PD and T2 weighted sequences with chemical/spectral presaturation are ideal to evaluate these relationships. The FOV and slice thickness reflect the quality of the coil used. The chemical/spectral presaturation sequence should be used with higher order shims to produce a more uniform suppression. If fat suppression is variable across the FOV a FSE/STIR sequence should be performed. Pre- and post-contrast T1 weighted sequences must cover the entire soft tissue component and area of muscle oedema. The sequences are generally FSE T1 weighted with chemical/spectral presaturation post-contrast. A minimum of two post-contrast scans should be obtained.

Soft tissue lesions are more common and range from trauma induced lesions to aggressive metastatic pathology. STIR FSE using a large FOV in either the coronal or sagittal planes to visualize the extent of the soft tissue oedema is a good option. It must include the whole muscle group from which it arises.

In congenitally dislocated hips (CDH) MRI can assist the surgeon in making an informed decision regarding treatment options. The evaluation of these patients falls into two categories and, unfortunately, both reflect

a late detection of CDH in the baby or young child. In the older child, pre-operatively it is necessary to outline the degree of cartilage coverage of the head of femur, the position and state of the labrum, signs of avascular necrosis, general position of the hip and local anatomy. These examinations should include a sequence (preferably coronal GRE) to evaluate the contralateral side. GRE with chemical/spectral presaturation and Tl weighted sequences in coronal oblique and transverse planes are sufficient to define the anatomy and sequelae of the dislocated hip. An additional sagittal/oblique GRE sequence using chemical/spectral presaturation may be necessary to define the femoral head further.

In babies, ultrasonography is often the only pre-operative imaging technique required.

MRI plays an important role post-operatively (preferably within 24 hours) to show hip alignment, early signs of avascular necrosis and possible causes for failed enlocation (usually inverted labrum). Coronal and axial chemical/spectral presaturation will cover all diagnostic contingencies. These patients, who are usually in hip spicas, are scanned with a small flexible coil used like a nappy between their legs

There has been a move in paediatric imaging to use diagnostic imaging that does not use ionizing radiation and for this reason 'whole body' screening procedures are performed to reduce the necessity for nuclear medicine studies. These whole body STIR examinations are as sensitive as nuclear medicine studies for the delineation and identification of neoplastic and infective lesions. The use of body diffusion weighted acquisitions fused to anatomical sequences provides images similar to PET.

Body imaging (Figures 15.25–15.29)

Body imaging in paediatrics follows many of the currently accepted adult clinical indications including liver, biliary (MRCP), bowel, urography, renal and pelvic applications (*see Liver and biliary system*). Many paediatric patients can be scanned using higher SNR coils such as the head coil, smaller body arrays or purpose-built coils. However, there is a higher conspicuity of respiratory artefacts. Smaller FOVs and thinner slices can usually be offset by more flexible coil options. The clinical acceptance of higher field strengths is an advantage to paediatric sites as the potential increase in SNR can be translated to higher through-plane resolution and, combined with parallel imaging techniques, shorter breath-hold times.

Peristaltic movement can be overcome by fasting the patient and using antispasmodic agents such as buscopan or glucagon. Pulsatile artefacts are reduced by careful placement of presaturation pulses, which are preferably concatenated. Respiratory artefacts are overcome by phase reordering, respiratory triggering, navigators, breath-hold and multiple NEX/NSA techniques. The most time-efficient option is the breath-hold technique but this requires cooperation from the child or anaesthetic control of breathing. Navigators are another option available to obtain motion reordered sequences. Unfortunately respiratory or diaphragm

15
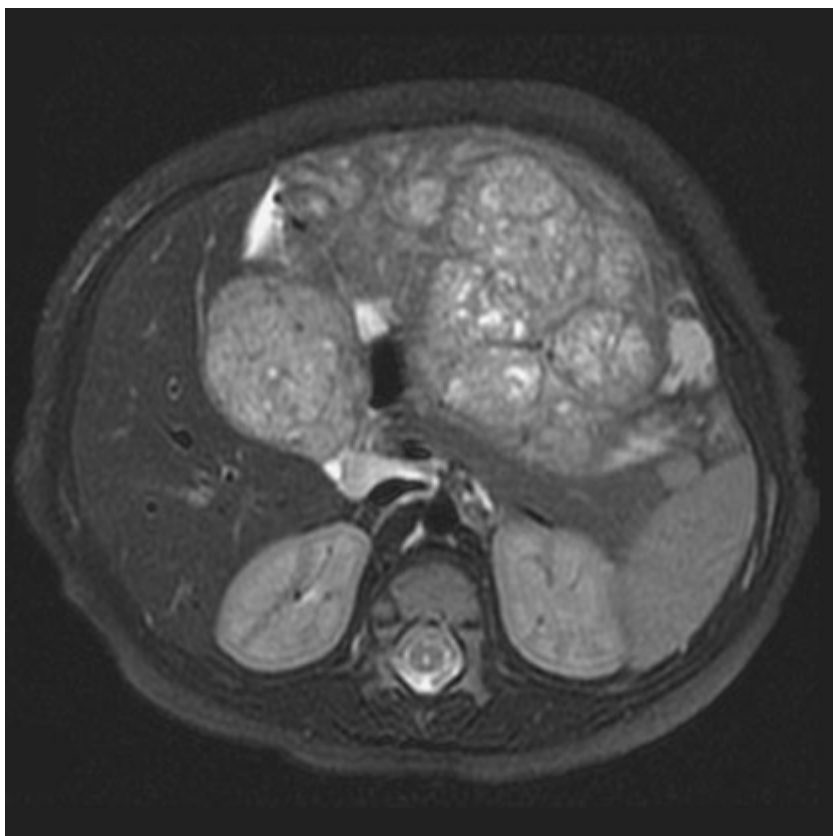
Figure 15.25 Axial FSE T2 weighted image with chemical presaturation demonstrating a hepatoblastoma.
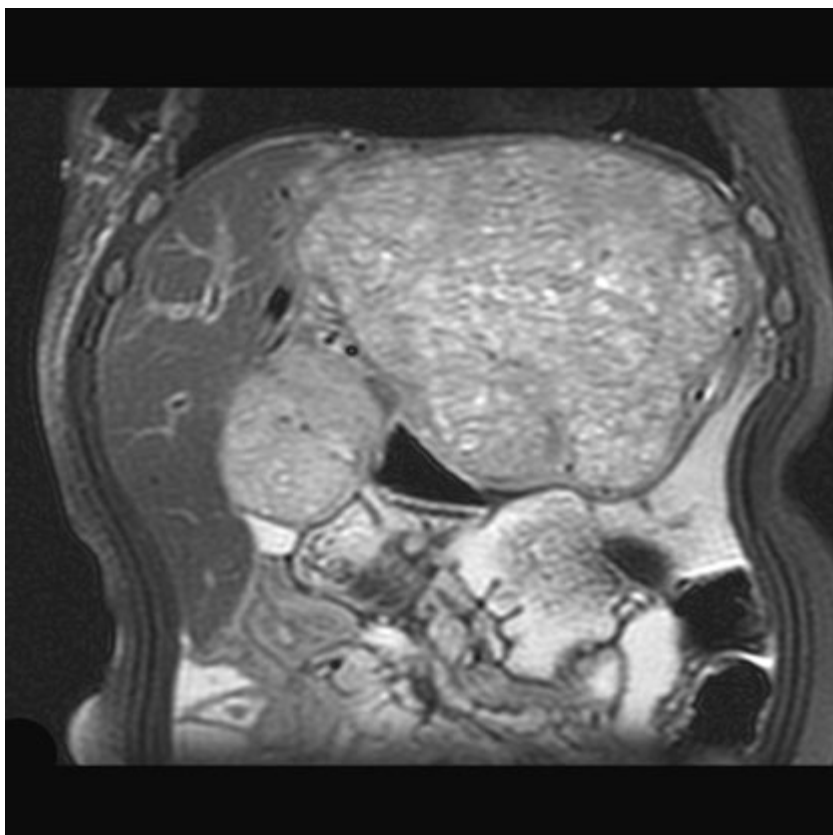
Figure 15.26 Coronal FSE T2 weighted image. Same patient as Figure 15.25.
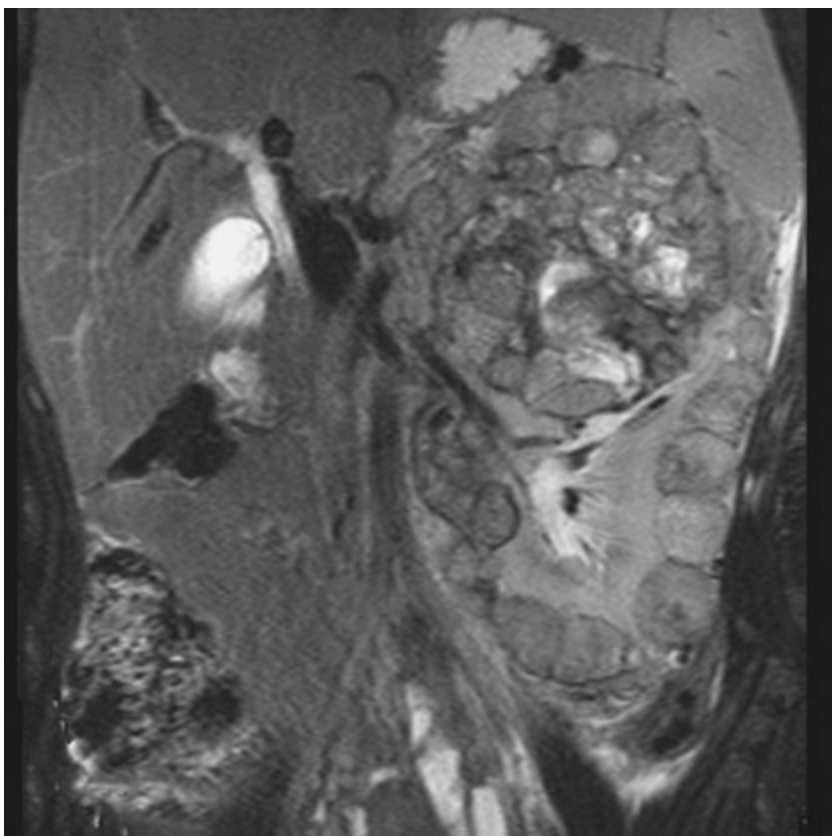
Figure 15.27 Coronal FSE T2 weighted image showing a large left renal tumour.
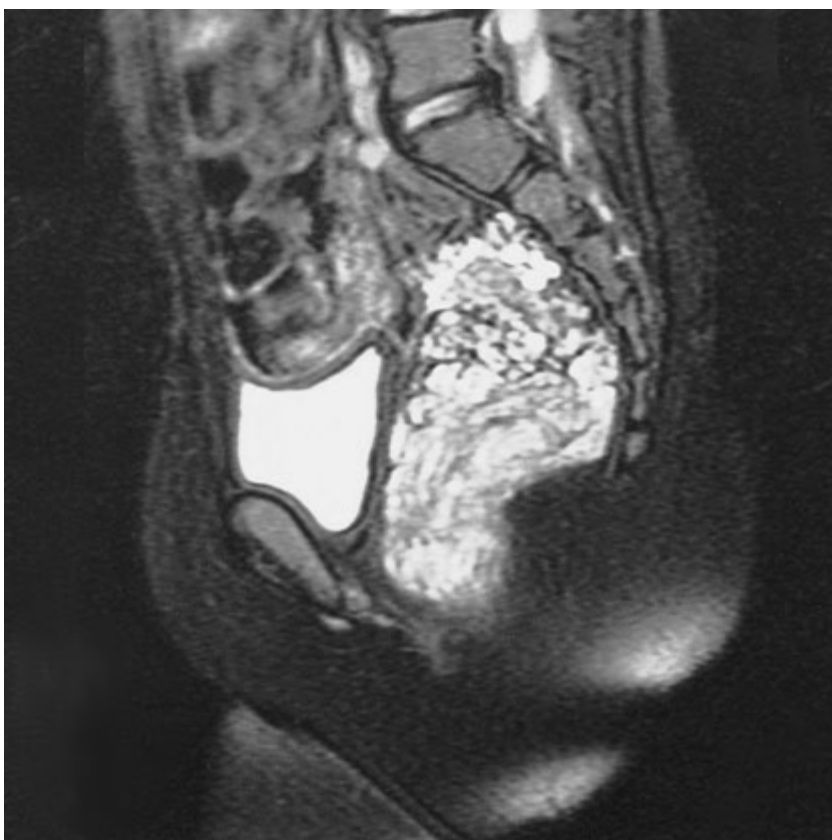
Figure 15.28 Sagittal FSE T2 weighted image with chemical presaturation of the pelvis showing a rectal vascular anomaly.

15

Figure 15.29 Whole body STIR image.

gated acquisitions require a relatively stable respiratory pattern that may be difficult for children to comply with. Chemical/spectral presaturation, IR-FSE T2 weighted, multishot SE-EPI and Tl weighted in-phase fast GRE (2D or interpolated 3D) breath-hold sequences cover most clinical applications. The choice of chemical/spectral suppression or IR-FSE T2 weighted sequences depends on the quality of the suppression technique, the presence of large air–tissue interfaces and the flexibility of individual sequences. In some long ETL, SS-FSE or HASTE sequences, SAR limits may be exceeded.

In patients where it is not possible to breath-hold, respiratory triggered T2 weighted sequences should be utilized. Respiratory triggering is inherently time inefficient and requires a relatively constant respiratory rate, but image quality is superior to other methods. Triggering, which requires some form of respiratory feedback to initiate the scans, can be accomplished by using navigator echoes, bellows or capnography. Bellows are clinically accessible but care must be taken when positioning them so as not to compromise respiratory action; many vendors are now offering a paediatric type bellows .

As in adults the preference for T1 weighted imaging is the dual echo (in-phase/out of phase) incoherent GRE sequence. The addition of spectral presaturation to the in-phase incoherent (spoiled) T1 weighted fast GRE is ideal for post contrast imaging and provides excellent time-efficient anatomical coverage. Conventional TI weighted phase reordered multiple NEX/NSA techniques using chemical/spectral presaturation provide a diagnostic scan where breath-holding is not possible. With the improvement of the diagnostic accuracy of multi-slice CT many MR centres that perform a large number of abdominal imaging often use breath-hold interpolated 3D incoherent, combined with parallel imaging, to provide higher resolution thin slice acquisitions The addition of spectral presaturation enables multi-phase post contrast examinations similar to CT.

The use of DWI in the body enables MR examinations of the liver and kidneys to increase the diagnostic specificity of MR. The *b* value is considerably less than the value chosen for imaging of the brain (0/150/350 s/mm^2). A standard liver examination should include T2 weighted acquisitions (coronal and axial), axial dual echo GRE, liver diffusion and a multiphase 3D breath-hold acquisition.

Pelvic MR imaging is performed for congenital anomalies of the ureto-genital system, rectal anomalies and abscesses (Crohn's disease) and tumours such as rhabdosarcomas. As in adult pelvic imaging, the scan planes for paediatric pelvic examinations should be performed parallel and perpendicular to the anatomy of interest. There are, however, a few modifications in paediatric imaging. In general, patients are scanned supine but in selected cases (anal anomalies such as imperforate anus), the patient may be scanned prone. When imaging muscle groups (e.g. levator ani), a proton density, chemical/spectral suppressed sequence is obtained parallel to the true anatomical course of the muscle group. When evaluating patients for incontinence it may be necessary to pass a non-inflated Foley catheter into the rectum.

15

The new MR techniques associated with body imaging are renal and bowel imaging. The evaluation of the complete renal system is a normal examination in paediatrics. Many investigators have developed techniques for renal function and MR urography. This examination is an extension of techniques used in MRCP. The evaluation of inflammatory bowel disease uses a combination of 3D GRE, single shot fast spin echo and Balanced GRE based sequences. It is necessary to use Buscopan to reduce peristaltic motion. There are many types of bowel contrast suitable for both negative and positive techniques such as Sorbitol/water combination, vegetable gum based solutions and high fibre substances such as Metamucil. The use of isotropic voxels for 3D balanced GRE allows for mulitplanar reformations essential for delineation of small abnormal segments of the small bowel.

Cardiac imaging (Figures 15.30–15.32)

Cardiac imaging is now an accepted part of the evaluation of congenital heart disease, anomalies of the great vessels and cardiomyopathies. MRI has progressed from essentially a diagnostic tool of morphology and

15

Figure 15.30 Sagittal/oblique cine image through the aorta demonstrating mild coarctation.
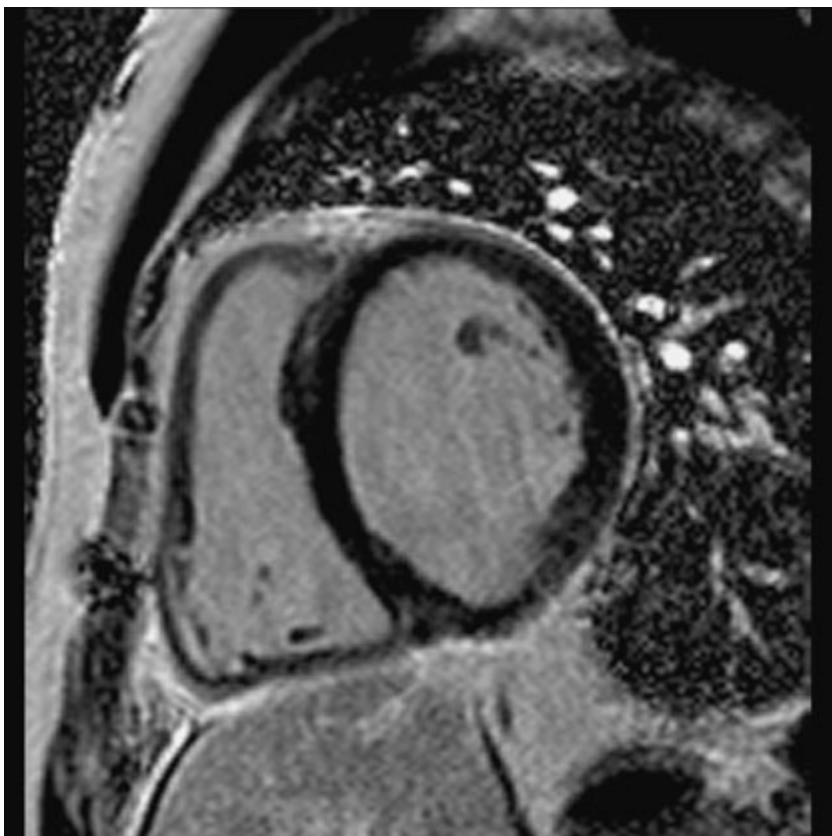
Figure 15.31 Short axis phase sensitive delay image.
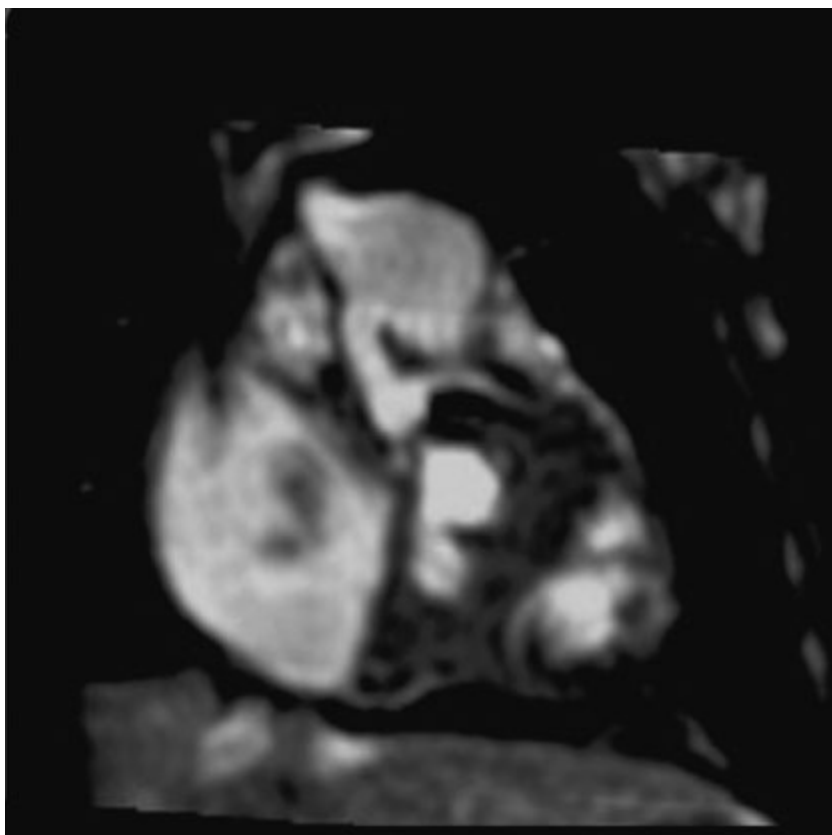
Figure 15.32 3D balanced GRE showing the left coronary artery in a 3-month-old child.

15

function to one that encompasses all aspects of cardiology (morphology, function, perfusion and viability). It is imperative if MRI is successfully to compete with echo and the catheter laboratory examinations that a planned examination protocol is utilized. This relies upon a good flow of information from cardiology to the MR team.

The most common examinations used to involve imaging the aortic arch (for vascular rings and hypoplastic arch) and descending aorta (for coarctation) but now MRI is providing information related to many complex congenital anomalies such as Fallot's tetralogy and hypoplastic left heart. With improvement in MR technology there has been a gradual decline in the amount of cardiac catheterization required in these complex cases. Historically these examinations have been performed using a combination of black blood or bright blood sequences but there is a trend in the literature for the bright blood sequences to be used for the majority of cases. Optimal black blood images can be obtained using dual-inversion FSE sequences to visualize associated anatomy such as the trachea. In children with a high heart rate above 120 beats per minute it is necessary to acquire black blood imaging over two R–R periods.

All cardiac imaging should be performed using breath-hold sequences or, if this is not appropriate, using respiratory triggering. In children that are sedated or incapable of breath-holds then there are several options to improve the diagnostic accuracy of the sequences including the use of multiple NEX/NSA, which average out motion and navigator pulses to track diaphragm motion.

Cardiac triggering is essential for high-quality images of the arch and great vessels. The most consistent results are obtained using ECG triggering but peripheral gating can be used (see *Gating and respiratory compensation techniques* in Chapter 5).

The protocol for vascular rings should include axial and coronal (contiguous < 3 mm) bright blood images and a contrast-enhanced 3D breath-hold MRA sequence. Some centres prefer to acquire the axial images using black blood techniques to identify the oesophagus and trachea. Ideally the contrast enhanced MRA for the pulmonary vascular tree and aorta should be gated to reduce partial volume effects but, even with the advent of very short TEs, this may not be practical. Due to the relatively small FOV and non specialist arrays, CEMRA may not be able to utilize the capabilities of parallel imaging fully. If it is not practical to give contrast, then an axial bright blood segmented K space fast GRE, small FOV series should be acquired.

Evaluation of the arch and descending aorta in cases of coarctation requires axial, sagittal/oblique and coronal/oblique imaging. Axial images are acquired first and then used as the planning scans for the sagittal and coronal obliques. Sagittal/oblique planes are necessary to view the arch and descending aorta (candy handle/walking stick view). Due to the size of the aorta, these should be obtained with thin slices. It is essential to align the slices so that they transect the ascending and descending aorta. A common mistake is to prescribe slices from an image that only demonstrates these two points. A more superior slice, at the angle of the aortic arch, will provide a more accurate alignment. The coronal obliques are

15

obtained perpendicular to the sagittal. It is essential that phase contrast cine sequences be performed that can be used to verify flow rates. These should be obtained superior and distal to the coarctation point.

In cases of suspected aneurysm, formation bright blood cine images should be acquired. As in the evaluation of vascular rings, the primary bright blood series is performed using contrast-enhanced MRA with a late phase for collateral vessels. Unlike adult cardiology where evaluation of the left ventricle and coronary arteries is the primary concern, the majority of congenital cardiac MRI is associated with the right ventricle and pulmonary arteries. One of the major difficulties in evaluating congenital heart disease is the orientation of the imaging planes. There are several techniques for determining the correct anatomical planes for the RVOT, LVOT, pulmonary arteries, vascular shunts and venous drainage. The simplest technique is to perform thin slice SS-balanced GRE in the axial plane through the entire heart and perform multi-planar reformations, which can be translated into imaging planes for acquisition of higher resolution scans. The second is to use the real-time capabilities of the system to navigate through the heart; however, this can often be confusing as technologists 'lose their way' and become disorientated. The third method is to use free breathing navigator based 3D BGRE sequences to obtain a slab of cardiac tissue and reformat.

MRI plays a significant role in the evaluation of cardiomyopathies, cardiac tumours and arrhythmic right ventricular dysplasia. These examinations use a combination of bright blood functional imaging, black blood morphological sequences, perfusion and viability.

Foetal MRI (Figure 15.33)

Foetal MRI represents one of the most dynamic forms of paediatric MR imaging. In general terms we have always had the capability to perform foetal MR examinations but have been limited by scan times thus resulting in patient motion and a lack of spatial resolution. The improvement in techniques such as SS-FSE and BGRE have enabled us to take a snap shot of the foetal anatomy reducing the effects of patient motion.

Foetal MRI is not a primary referral tool but must be used in conjunction with a tertiary referral based ultrasound with very specific clinical criteria that has the potential to assist the primary care physicians to make decisions regarding the health of the pregnancy and the course of treatment post delivery. Many centres around the world use foetal MRI as a road map to foetal surgery. The timing of the examination will reflect the clinical question and depend upon the gestational age and the immediate treatment plan. Imaging prior to 20 weeks is extremely challenging due to the size and mobility of the foetus. Some European centres sedate the mother, which also affects the foetus, further reducing the effects of patient movement. To further reduce subject motion all images should be acquired in suspended respiration. MR has a very high diagnostic sensitivity and specificity for lesions involving the neuroaxis, head/neck tumours

15

Figure 15.33 Sagittal T1 weighted image showing a foetal lymphatic lesion.

and congenital anomalies, lung lesions, diaphragmatic hernia, renal and pelvic anomalies and skeletal malformations. Real-time balanced GRE can also be used to evaluate foetal motion including swallowing and gross cardiac function.

The basic foetal brain examination should include thin slice (maximum 3 mm) T2 weighted sequences in all three orthogonal planes. Most centres rely on SS-FSE because of the familiar signal characteristics of the brain. These acquisitions require a maximum in-plane spatial resolution of 1 mm × 1 mm so that gyral malformations and small cortical based lesions are evident. In addition to the T2 weighted sequences it is imperative to acquire a T1 weighted sequence, usually incoherent GRE sequence, to identify blood and calcium products. A susceptibility sequence such as a SS-EPI may also be used to define any blood products further. Some leading centres also include DWI and MR spectroscopy to define any pathology further.

When evaluating the abdominal structures steady state free precession sequences have a more flexible K-space traversal scheme (Cartesian vs. radial), which have the potential to produce images with a higher spatial resolution. In abdominal imaging a T1 weighted sequence in all three

15

orthogonal planes is mandatory to identify the meconium within the bowel. Foetal imaging can be a challenge but with the appropriate preparation of the mother it is a worthwhile experience. Foetal MRI is, by definition, potentially a very stressful time for the mother so it is essential that centres performing foetal MRI spend the time counselling the mother regarding the scan, prepare her for the MR examination to reduce her anxiety and assist her to lie on the examination table in a comfortable environment.

Conclusions

Children and claustrophobic adults can present special challenges to the MR unit. Safety is the most important consideration. Whatever policy the centre adopts for scanning these patients, no expense should be spared to ensure their safety whilst they are unconscious in the unit. If it is decided that monitoring equipment or anaesthetist time is too expensive, then arrangements should be made to have these patients scanned at other facilities. In addition, it is important not to overlook the parents. It is easy to forget that parents are very anxious about the condition of their child and the outcome of the examination. Try to keep them continually informed and involve them as much as possible. All these measures should provide a safe, relaxed environment for paediatric examinations. Finally, the advent of motion sensitive correction, parallel imaging and ultrafast sequences may negate the need for sedation or general anaesthesia as the scan times are so short that even the most restless patient can be examined successfully.

Index

Note: page numbers in *italics* refer to figures, those in **bold** refer to tables